Adapting UK Dwellings for Heat Waves

Stephen Michael Porritt B.Sc (Hons.)

Submitted in partial fulfilment of

the requirements for the degree of

DOCTOR OF PHILOSOPHY

Institute of Energy and Sustainable Development

De Montfort University, Leicester

March 2012

Abstract

The emphasis for UK dwelling refurbishment to date has centred on reducing heating energy use. However, there has been increasing evidence pointing to the need for a more holistic approach.

Many existing dwellings already experience overheating during hot weather periods. Climate change projections predict increases in both the frequency and severity of extreme weather events including heat waves such as the one in August 2003, which is estimated to have claimed the lives of over 35,000 people throughout Europe, including 2,000 in the UK. Demand for housing exceeds the supply of new stock and it is estimated that over 70% of the dwellings that will be in use in 2050 have already been built. Therefore existing dwellings will require adaptation to provide more comfortable and safe environments, to reduce both summertime overheating and heating energy use.

In this research, dynamic thermal simulation computer modelling was used to assess and rank the effectiveness of selected single and combined passive interventions (adaptations) on dwelling overheating during a heat wave period. Simulations were also carried out to assess the effect of those interventions on annual space heating energy use. Four distinct dwelling types were selected to represent the housing stock in London and South East England, producing seven modelling variants: 19th century end and mid-terraced houses; 1930s semi-detached house; 1960s ground, mid and top floor flats and a modern detached house. Simulations were carried out for two different occupancy profiles and four building orientations and the cost of interventions was also considered in the analysis. The first occupancy profile assumed a 'typical' family who left the dwellings unoccupied during the daytime, the second assumed residents who were at home all the time (e.g. elderly or infirm).

Of the dwelling types studied the 1960s mid and top floor flats and the modern (2006) detached house (Tier 2) experienced more than twice as much overheating as the other dwelling types (Tier 1). Tier 2 dwellings were "harder to treat" and unlike Tier 1 dwellings their overheating exposure could not be eliminated using the selected passive interventions. It was possible to substantially reduce overheating and annual heating energy use of Tier 1 dwellings at moderate cost, whereas the costs for retrofitting Tier 2 dwellings were estimated to be many times higher. The results demonstrated that overheating exposure can be significantly greater for residents who have to stay at home during the daytime and they should not, where possible, be housed in the most vulnerable dwellings.

External window shutters were found to be the single most effective intervention for overheating reduction in most of the dwelling types considered, typically resulting in a 50% reduction in overheating exposure. The exception was the 19th century terraced houses, where applying a solar reflective (high albedo) coating to the solid

external walls was often more effective. In some cases the addition of insulation increased overheating and external wall insulation consistently outperformed internal wall insulation when considering the effect on overheating, though the latter could be effective as an element of combined interventions.

Adaptation should therefore be considered together with mitigation, both in design practice and in regulations. If existing dwellings (for example the 19th century terraced houses) are retrofitted for energy efficiency, without considering summer use, overheating could increase dramatically. Subsequent corrective measures could be costly and energy efficiency may suffer as a result.

This research builds on previous publications and research to generate systematic, quantitative and holistic guidance for retrofitting UK dwellings to reduce overheating risk during heat waves, whilst minimising annual space heating energy use and considering the cost of retrofit. An interactive retrofit advice toolkit has been developed (and made publicly available) as part of the research, which allows selection of the best performing interventions within a given budget. Recommendations for further development of the research are also suggested.

Contents

List of Figures

List of Tables

Abbreviations

ACH	Air change rate - air changes per hour
ARCC	Adaptation and Resilience in a Changing Climate coordination network
BRE	Building Research Establishment
BS	British Standard
CIBSE	Chartered Institution of Building Services Engineers
CLG	U.K. Government Department for Communities and Local Government
CREW	Community Resilience to Extreme Weather project
CTF	Conduction Transfer Functions (EnergyPlus heat balance algorithm)
DEFRA	The Department for Environment, Food and Rural Affairs
DSA	Differential sensitivity analysis
DSY	Design Summer Year (simulation weather file)
DTM	Dynamic thermal modelling
EHCS	English House Condition Survey
EHS	English Housing Survey
EMS	Energy Management System (EnergyPlus)
EPSRC	Engineering and Physical Sciences Research Council
Erl	EnergyPlus Runtime Language
GUI	Graphical User Interface
IDF	Input Data File (EnergyPlus)
IES	Integrated Environmental Solutions Virtual Environment software
IESD	Institute of Energy and Sustainable Development
IPCC	Intergovernmental Panel on Climate Change

MCA	Monte Carlo analysis
ONS	Office for National Statistics
PCM	Phase Change Material
SAP	Standard Assessment Procedure
SBEM	Simplified Building Energy Model
SHGC	Solar Heat Gain Coefficient
SSA	Stochastic sensitivity analysis
TRY	Test Reference Year (simulation weather file)
UHI	Urban Heat Island
UKCIP	United Kingdom Climate Impacts Programme

Author declaration

During the period of registered study leading to the preparation of this thesis the author has not been registered for any other academic award or qualification.

The material is the author's own work and has not been submitted wholly or in part for any other academic award or qualification.

Stephen Michael Porritt

March 2012

Acknowledgements

This research was part of the CREW project (Community Resilience to Extreme Weather) funded by the EPSRC (grant number EP/F036442/1) and their support is gratefully acknowledged.

I would like to thank my supervision team, Professor Li Shao and Dr. Paul Cropper at the Institute of Energy and Sustainable Development (IESD), De Montfort University, Leicester and Dr. Chris Goodier at Loughborough University. They have always been available to provide support, encouragement and critical appraisal of my research.

During the research project a web toolkit was developed to present the research and this has been included in Appendix B. Some of the initial html coding for the single intervention part of toolkit was carried out by June Wang, a freelance web designer. Dr. Paul Cropper discovered the Highcharts software, which allows the scatter plots developed during the research to be presented in an interactive way. I am also grateful to Dr. Cropper for help with other aspects of the toolkit web coding.

Friends and colleagues within the IESD have also listened to my ideas and provided valuable advice, in particular: Vic Hanby, Stefan Smith, Yi Zhang, Sherif Ezzeldin, Ivan Korolija, Graeme Stuart, Rob Liddiard, Denis Fan, Miaomiao He, Michael Coleman, Neil Brown, Peter Mallaburn, Caroline Wilson, Mark Lemon, John Mardaljevic, Birgit Painter, Carl Holland and Jim Parker. Apologies to anyone I have missed.

Finally, I must thank my parents and most importantly my wife, Jacqui, for her constant support and encouragement and for allowing me to give up my job and make this career change.

Chapter 1

Introduction

1.1 The need for dwelling retrofit guidance

The main focus for dwelling refurbishment to date has centred on reducing heating energy use and associated carbon emissions. The UK Government has targeted energy efficiency resources through schemes such as Warm Front in the past and the soon to be launched Green Deal (DECC, 2010b). Organisations including the Energy Saving Trust, Which? and the energy utility companies also promote energy efficiency improvements for housing.

However, the UK climate is warming and projections from the UK Climate Impacts Programme and the Met Office (Murphy et al., 2009) predict increases in mean temperatures, accompanied by more frequent and more intense extreme weather events, including heat waves. In August 2003 a severe heat wave caused the deaths of over 35,000 people around Europe, more than 2,000 of which were in the UK (Johnson et al., 2005). Most of the victims were elderly and vulnerable, living in major cities. Temperatures in London were increased by the urban heat island effect and were up to 10 °C higher than surrounding rural areas (Greater London Authority, 2010). The Department of Health and the Health Protection Agency predict that a 9-day heat wave averaging 27 °C in South East England would lead to over 3,000 immediate heat related deaths (Health Protection Agency, 2008).

New houses are not being constructed in the UK at a rate to satisfy housing demand and much of the current housing stock will still be in use for many decades. It is estimated that over 70% of the dwellings that will be occupied in 2050 have already been built (Boardman et al., 2005). Since that report was published the economic downturn has reduced new building rates further, therefore retrofit of existing dwellings will be central to meeting the energy and comfort needs of the UK population. Davies and Oreszczyn (2012) warn that energy efficiency improvements could increase the risk of summertime overheating, with consequential risks to health. Future retrofit decision making therefore needs to take account of both winter energy savings and reducing summer overheating to provide safe and comfortable dwellings.

The Institute of Environmental Management and Assessment (2009) reported that 90% of local government departments were planning for adaptation to climate change. Individual UK Government Departments have also recently published their latest climate adaptation plans (U.K. Government, 2011), signalling a shift in emphasis towards policies which combine mitigation with adaptation. However, current retrofit guidance does not provide the detailed quantitative information required to meet this need. A report for the Three Regions Climate Change Group states: "uptake of climate change adaptation measures is low because of the lack of information and awareness about adaptation options" (Arup, 2008).

The Chartered Institution of Building Services Engineers has published guidance, addressing specifically the impact of climate change on the indoor environment (CIBSE, 2005). Overheating adaptation guidance is also available from EST (2005) and Arup (2008), amongst others. However, the advice is limited in terms of the interventions considered, the effect of dwelling orientation and consideration of different types of occupants.

In response to this need for more detailed quantitative information the Engineering and Physical Sciences Research Council (EPSRC) funded a range of projects, including CREW (2011) - Community Resilience to Extreme Weather. This research forms Programme Package 1 of the CREW Project: Identification and assessment of coping measures for dealing with extreme weather events.

1.2 The aims and objectives of the research

The aim of the research is to provide holistic retrofit guidance for decision makers, designers and homeowners by investigating the effects of a range of passive interventions applied to dwellings.

The research considers the impact of interventions on both overheating during a known heat wave period and on annual space heating energy use. This research expands on previous published work by providing detailed quantitative information for a range of dwelling types and building orientations. Comparing the effects of overheating on different types of occupant has also been absent in previous publications, which is addressed in this research. Intervention costs are also included in the analysis to allow selection of the best performing interventions within the available budget.

Selected passive interventions are assessed, both individually and combined. The term interventions covers a range of physical additions or adaptations to the building fabric, including insulation and solar control, as well as behavioural changes such as modifications to ventilation control. Only passive interventions have been considered in this research as they do not directly contribute to building energy consumption and its associated carbon emissions.

To achieve the research aims the following objectives were set:

- Identify representative dwelling types for London and South East England (CREW project study area).
- Investigate the effectiveness of a range of passive interventions for reducing overheating during a heat wave period in the targeted dwellings using computer simulation.
- Repeat the simulations for different occupancy profiles and dwelling orientations.
- Carry out simulations for combined interventions.
- For each case determine the annual space heating energy use.
- Investigate the typical installed costs of the interventions.
- Combine all of the above to produce a retrofit toolkit, which allows easy selection of the best performing interventions for each dwelling, orientation and occupancy profile at a given budget.

1.3 Outline of the thesis

- **Chapter 2** presents the background to the research, starting by looking at heat waves and their effect on health and thermal comfort as well as looking at current methods of measuring overheating in dwellings. Sources of information on housing stock and occupancy profiles are presented, which are used later (Chapter 3) to construct the simulation models. Dynamic thermal modelling is briefly introduced (discussed in more detail in Chapter 5) and the chapter concludes with a review of existing research and guidance on overheating in dwellings.

- **Chapter 3** uses data from a government housing database to select representative dwellings for modelling. The simulation model plans and construction details are presented, including the internal gains and occupancy profiles.
- **Chapter 4** discusses the range of passive interventions selected for modelling and presents the details used in the simulations.
- **Chapter 5** discusses the choice of software for dynamic thermal modelling and the methods used to conduct the large scale parametric simulations required.
- **Chapter 6** is the first of the results chapters and presents the base case simulation results for each dwelling type, orientation and occupancy profile. The worst performing dwelling type for overheating is identified for detailed analysis.
- **Chapter 7** presents the simulation results for the effect of single and combined interventions on the top floor flat, identified in the previous chapter as the worst dwelling type for overheating. The effect on space heating energy use and the cost of interventions is also presented and a retrofit toolkit to enable easy interrogation of the results is introduced.
- **Chapter 8** contains the simulation results for all the other dwelling types, for both single and combined interventions.
- **Chapter 9** discusses the results presented in the previous three chapters, comparing the effect of interventions across dwelling types, orientations and occupancy profiles, identifying the key messages from the research.
- **Chapter 10** presents the conclusions with suggestions for further research.

Chapter 2

Background

2.1 Foreword

During the course of this research many decisions had to be made, including selection of dwellings, choice of simulation software and determining the most appropriate overheating criteria for presenting the results. This chapter explores the background research undertaken to make these and other decisions.

The chapter begins by looking at the definition of heat waves before exploring overheating threshold temperatures and the effects on health. Housing stock and occupancy profile databases are introduced, which are used later (Chapter 3) to construct the models for simulation and the choices for weather data that can provide heat wave periods for simulation are investigated.

This chapter also provides a review of current guidance and academic research into dwelling overheating to identify the gaps in knowledge which this research aims to address.

2.2 Heat waves

2.2.1 Definition

The UKCIP defines a heat wave as *A prolonged period of excessively hot weather, which may be accompanied by high humidity*, also stating that *There is no universal definition of a heatwave; the term is relative to the climate in the area with a locally identified threshold temperature* (UKCIP, 2011). Other definitions are more specific, for example the World Meteorological Organisation suggest a heat wave duration index for mid latitude areas based on the number of days over 5 consecutive days where the maximum temperature exceeds the average historical (1961 - 1990) maximum temperature by 5 °C (Frich et al., 2002).

The World Health Organisation have attempted to define heat wave days as those in which the apparent maximum temperature[1] and the minimum temperature are over the 90th percentile of the monthly distribution for the specific city for at least two days (Menne and Matthies, 2009).

In the UK the Meteorological Office (Met Office) provides simple heat wave threshold definitions, which vary from region to region, as part of their weather warning information (UK Meteorological Office, 2011b). In each case a heat wave is deemed to occur if certain day and night threshold temperatures are exceeded for two or more consecutive days. For London the day threshold temperature is 32 °C and the minimum night temperature is 18 °C, often referred to as the 32-18-32 rule. The thresholds for South East England are slightly lower at 31 °C (day) and 16 °C (night) and further north they are lower still, for example in North East England the thresholds are 28 °C (day) and 15 °C (night) .

[1]Apparent temperature is defined in Menne and Matthies (2009) as a measure of relative discomfort, combining heat and high humidity

2.2.2 Significant UK heat waves

A UK Government report (McGregor et al., 2007) acknowledges that there have been three major heat wave periods in the UK during the last 35 years: late June to early July 1976, late July to early August 1995 and early to mid August 2003. There were also a series of short heat wave periods during July 2006 that exceeded the Met Office heat wave threshold temperatures, triggering the Heat Wave Plan for England (National Health Service, 2011). The plan was developed to provide guidance for coping with heat waves following the events of 2003.

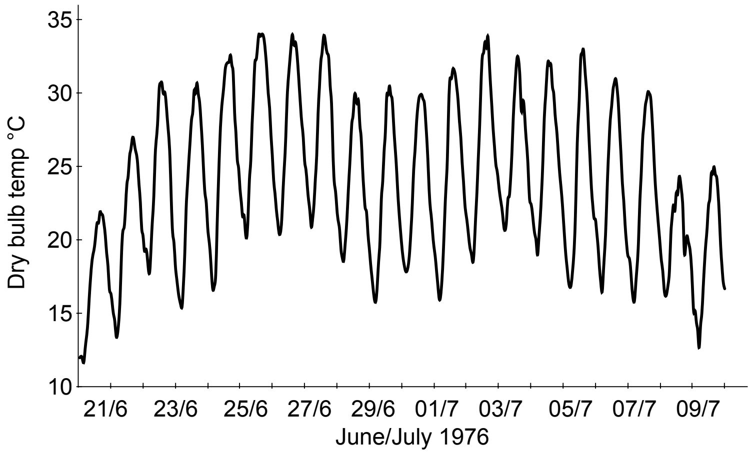

Figure 2.1 – 1976 heat wave (London Heathrow temperature)

Using the Met Office 32-18-32 heat wave definition for London (Section 2.2.1), the 1976 heat wave (Figure 2.1) started on the 25th June and lasted four days before a slightly cooler (but still very hot) period occurred from the 29th June to the 2nd July. Temperatures then rose again from the 3rd to the 5th July. The hottest day at London Heathrow was the 26th June, where the daytime temperature peaked at 34 °C with the following nighttime temperature not dropping below 20 °C.

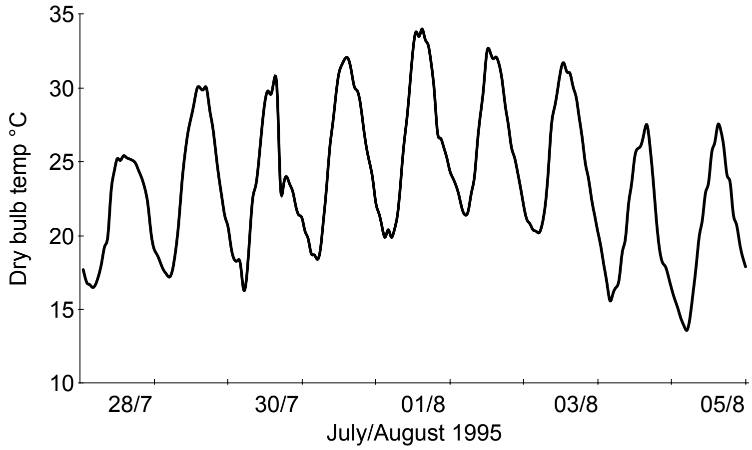

Figure 2.2 – 1995 heat wave (London Heathrow temperature)

The 1995 heat wave (Figure 2.2) was of high intensity but lasted just four days from the 31st July to the 3rd August. The peak daytime temperature at London Heathrow was 34 °C on the 1st August, with the following night temperature not dropping below 21 °C.

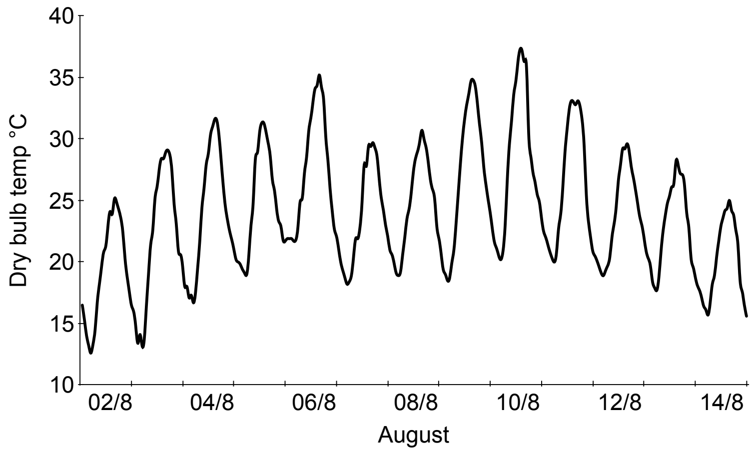

Figure 2.3 – 2003 heat wave (London Heathrow temperature)

The 2003 heat wave (Figure 2.3) is the most notable of the severe heat waves from the last 35 years because of the high mortality experienced throughout Europe. Temperatures began to rise in early August 2003 and the heat wave started around the 4th, peaking at over 37 °C at London Heathrow on the 10th. The daytime Met Office heat wave definition threshold temperature for London (32 °C) was not exceeded on some of the days, but nighttime temperatures remained very high, not falling below 18 °C. The 2003 heat wave is generally accepted to have lasted nine or ten days from the 4th to the 12th or 13th of August.

Image removed from electronic version of the thesis to comply with copyright - see reference

Figure 2.4 – UK maximum temperatures 10th August 2003 (reproduced from UK Meteorological Office (2011a))

Figure 2.4 contains a map of maximum UK temperatures on the peak heat wave day (10th August 2003) from the UK Meteorological Office (2011a). The map shows that the highest temperatures were concentrated in London and South East England.

2.2.3 Heat waves and climate change

The Intergovernmental Panel on Climate Change (IPCC) state in the Technical Summary for their Fourth Assessment Report that *Heat waves become more frequent and longer lasting in a future warmer climate* (Solomon et al., 2007). For UK specific climate projections the UK Climate Impacts Programme (UKCIP), in conjunction with the Met Office Hadley Centre, published its first climate change projections in 1998, which were substantially updated in 2002 and again in 2009. The latest (UKCP09) projections (Murphy et al., 2009) include, for the first time, probabilistic projections for three climate change scenarios: High, Medium and Low. The Medium scenario assumes rapid economic growth, world population growing and peaking in the middle of the 21st century before declining, the rapid introduction of new technologies and a balance between fossil and non-fossil energy sources. The High scenario is the same as the Medium, but assumes high fossil fuel use, whereas the Low scenario assumes a higher global focus on sustainability, reductions in material use and more clean and efficient technologies (Murphy et al., 2009).

UKCP09 provides projections for mean, maximum and minimum temperature; precipitation; humidity; cloud cover; net long and short wave radiation and sea level pressure. However, one significant weather variable is omitted. The projections do not include wind as a weather variable, which is required for constructing building simulation weather files. The projected summer temperature rises are of most interest for this research and Figure 2.5 shows the maximum daily temperatures for the UK in the 2080s assuming the medium emissions scenario.

Under this scenario the predicted rise in mean summer temperature for south east England is 3.9 °C by the 2080s, with a 50% probability (central estimate). The UKCP09 projections also predict more frequent and more intense heat wave periods, with drier summers and warmer, wetter winters. Using the UKCP09 Weather Generator for London Heathrow, assuming a medium emissions scenario, the central estimate predicts 27 days with temperatures over 28 °C by the 2080s, compared with 2 days over 28 °C for the current climate (Jenkins et al., 2009b). Figure 2.6 illustrates the effect of shifting the temperature distribution due to climate change and how a modest shift in mean temperature leads to a significantly higher frequency of temperatures above overheating thresholds.

Image removed from electronic version of the thesis to comply with copyright - see reference

Figure 2.5 – Probability of mean maximum daily temperature rise under medium emissions by the 2080s (Reproduced from Murphy et al. (2009))

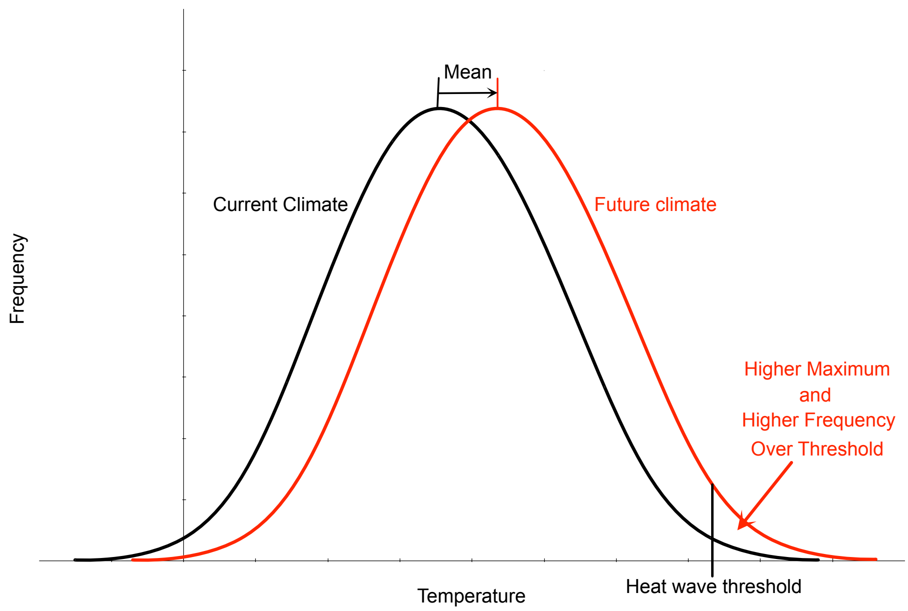

Figure 2.6 – Change in temperature distribution with climate change (adapted from Solomon et al., 2007)

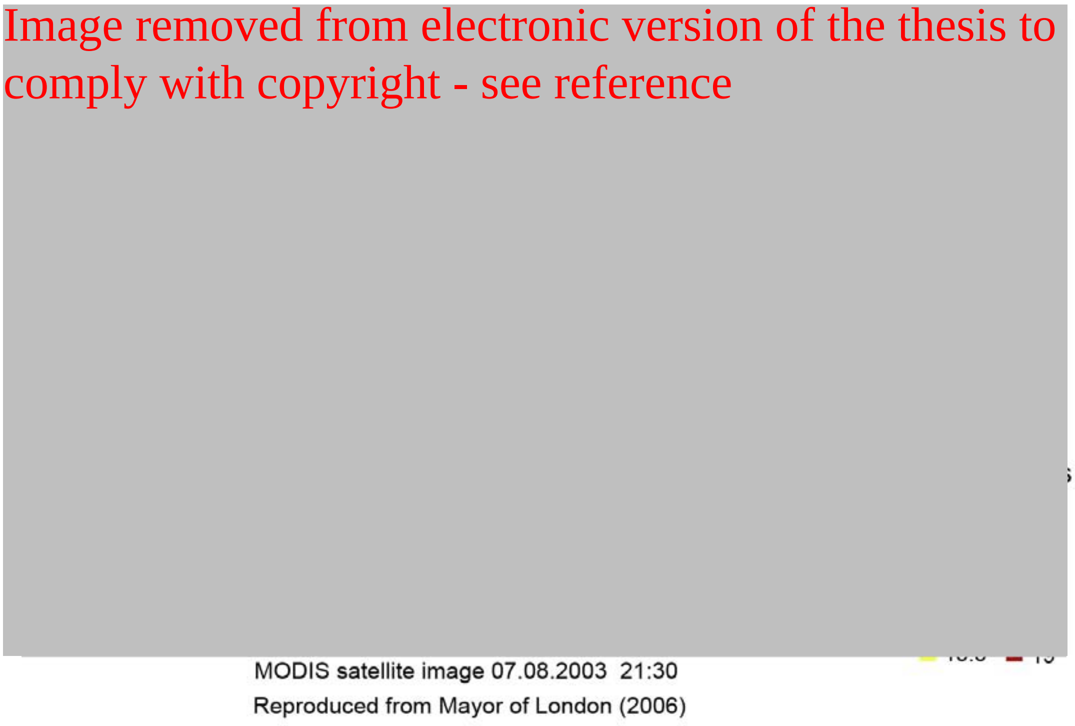

Figure 2.7 – London UHI during 2003 heat wave

2.2.4 Urban heat islands

The urban heat island effect (UHI) produces elevated night time temperatures in larger urban areas, compounding the overheating problem during heat wave periods. The lack of cooler night air makes it more difficult to remove the heat built up during the daytime and cool the building fabric. Night temperatures in central London were up to 8 or 9 °C higher than a rural reference location during the 2003 heat wave (Mayor of London, 2006). The UHI effect diminishes as the distance from the city centre increases and a survey in 1999 found an average UHI increase of 2.8 °C for London compared to surrounding rural areas (Watkins et al., 2002). Figure 2.7 shows the temperature distribution across London at 21:30 on one of the heat wave days in August 2003.

Two recent ARCC (Adaptation and Resilience in a Changing Climate) projects, LUCID and SCORCHIO, have investigated the effect of urban heat islands on building overheating and these are discussed in Section 2.9.1.

The suburban and semi-urban locations, where much of the London housing is found, are not in the core city centre heat island. Traditionally CIBSE weather files derived from London Heathrow Airport weather station data are used in simulations for London buildings. Figure 2.7 shows that the Heathrow area experiences comparable temperatures to much of the suburban areas around London. Research by Kolokotroni et al. (2005) proposed corrections to air temperature from the London Heathrow values of between -0.9 °C and +2.2°C for suburban and semi-urban locations, which vary by location and time of day.

2.3 Thermal comfort, overheating and health

2.3.1 Thermal comfort

A common definition of thermal comfort is *that condition of mind which expresses satisfaction with the thermal environment and is assessed by subjective evaluation* (ANSI/ASHRAE, 2010). ASHRAE devised a seven point scale from -3 (cold) to +3 (hot), with 0 being thermally neutral. The fact that thermal comfort is subjective means that some people will be more or less comfortable than others in the same environment. Fanger (1970) devised a thermal sensation index based on the predicted mean vote (PMV) of a group of individuals in an environment using the ASHRAE seven point scale. There will always be a certain percentage of people who are not thermally comfortable, whatever the environment, and Fanger developed a method of measuring the level of thermal discomfort through the percentage of people dissatisfied (PPD). The minimum PPD when the PMV = 0 is 5%, but this increases to 10% at PMV = ± 0.5 and 50% at PMV = ± 1. What is not clear from the PMV/PPD method is any indication of where the discomfort due to the thermal environment changes to a risk to health.

People are able to adapt to higher temperatures, particularly when they have some control over their environment and other factors, such as clothing. The Adaptive Principle states that:

> *If a change occurs such as to produce discomfort, people react in ways which tend to restore their comfort (Nicol et al., 2012).*

Section 2.3.4 discusses the approach to adaptive comfort threshold temperatures adopted in the latest international standards.

2.3.2 Thermal stress - health effects of high temperatures

Thermal stress is the point at which the environment starts to pose a risk to health either through heat or cold. If people who are not accustomed to hot environments are exposed to higher temperatures they will initially be stressed, but will acclimatise after a few days through both behavioural and physiological changes (Parsons, 2003).

ASHRAE (2009) consider 35 °C (at 50% relative humidity) to be the heat stress upper limit temperature for healthy adults, but notes that a 33% increase in deaths in the over 65 age group was observed during a heat wave in Illinois, USA, at a temperature of 29.5 °C (50% relative humidity). The Heat Wave Plan for England (National Health Service, 2011) warns that, for high risk groups in care homes or hospitals, there are risks to health (mostly due to respiratory or cardiovascular problems) if the temperature rises above 26 °C. Reduced sweating ability and impaired thermoregulation are identified as factors rendering the body more vulnerable to overheating. The plan also advises that cool rooms or cool areas should be provided in care homes and hospitals that do not exceed this temperature. The World Health Organisation lists a combination of factors that contribute to elderly heat wave vulnerability including pre-existing illnesses requiring drugs that may interfere with normal homeostasis; lack of awareness of becoming ill from the heat (possibly as the result of medication); lower fitness levels and reduced sweating ability (Koppe et al., 2004).

Figures published by the UK Environment Agency (McGregor et al., 2007) show that the 2003 heat wave had the highest social impact of the three major UK heat waves of the last 35 years (1976, 1995 and 2003), with excess deaths in Greater London of 44.7% for the 75-84 age group and 33.3% for all age groups. This compares to a 15% increase during the 1976 heat wave and a 16% increase during the 1995 heat wave. The Health Protection Agency and the Department of Health extrapolated data from the 1976 and 2003 heat waves to show that a 9-day heat wave averaging 27 °C in South East England could lead to over 3,000 immediate heat related deaths (Health Protection Agency, 2008). A study of heat waves in America by Gasparrini and Armstrong (2002) found that most mortality during heat waves was the result of adding together the effects of individual hot days, but did notice a small extra impact attributed to sustained high temperatures when heat waves last more than 4 days.

Image removed from electronic version of the thesis to comply with copyright - see reference

Figure 2.8 – Mortality against average temperature for London - reproduced from Hajat et al. (2002)

Hajat et al. (2002) investigated the link between high temperatures and mortality for London. Figure 2.8 shows how the mortality rate is high at low temperatures and falls to a minimum at an average temperature of around 17 °C, before starting to rise again from around 19 °C. Their findings suggest a linear relationship with a 5.7% increase in deaths for each 1 °C over 23.3 °C, but they also detected a sharper rise in mortality at very high average temperatures. The results also suggest that heat waves earlier in the summer, such as the one in 1976, have a greater impact than similar ones later in the year. This may be due to a lack of acclimatisation early in the year or could be the result of deaths that would have occurred later in the year being brought forward (Hajat et al., 2002).

It is not just extreme heat that causes increased mortality and illness during heat waves. Research by Stedman (2004) following the 2003 heat wave estimated that 21-38% of the excess deaths could be attributed to increased pollution in the form of ozone and PM_{10} concentration. This could have implications for advice regarding exposure to the atmosphere outdoors and for the natural ventilation of buildings with outside air, especially in city locations where pollutant concentrations are highest.

The problem of heat stress illness and mortality in a future with more intense and more frequent heat waves will be compounded by an ageing population. Many of these elderly and infirm citizens will be occupying their dwellings during the hottest parts of the day.

2.3.3 Overheating threshold temperatures

Overheating threshold temperatures are currently the subject of much debate, with organisations such as the Chartered Institution of Building Services Engineers (CIBSE), the Building Research Establishment (BRE) and the Health Protection Agency (HPA) recently holding workshops to gather knowledge and produce better informed design guidance and regulations.

For most types of buildings, including dwellings, there are no statutory overheating threshold temperatures. The exceptions are regulations governing thermal conditions for schools, laid down in Building Bulletin 87 (DfES, 2003), which allows the internal summer temperature to deviate by +/- 4 °C from a target temperature of 24 °C, i.e. a maximum temperature of 28 °C. It is deemed acceptable for this to be exceeded for 80 hours during the summer term, although no upper temperature limit is stated. The Department of Health (2007) also specify a peak summertime internal temperature for patient areas in hospitals of 28 °C, which should not be exceeded for more than 50 hours in a year, again with no upper limit temperature.

Part L of the Building Regulations (Office of the Deputy Prime Minister, 2006b) requires an overheating risk assessment of any new dwelling by using SAP (Standard Assessment Procedure) worksheets at the design stage (Building Research Establishment, 2010). For the risk assessment the gains (solar and internal) are used with the ventilation heat loss, the dwelling thermal mass parameter and the mean local summer external temperature to obtain a threshold internal temperature. If this threshold internal temperature is greater than 23.5 °C the dwelling is deemed to have a high likelihood of high internal temperatures during hot weather. However, there is no indication from the assessment as to how high the internal temperature may go.

CIBSE Guide A - Environmental Design (CIBSE, 2006) provides recommended operative temperature ranges for different types of mechanically ventilated and free running buildings. The operative temperature (also known as the dry resultant temperature) combines the room air temperature and mean radiant temperature from the room surfaces to provide a thermal comfort index temperature. It can be calculated using the formula in Equation 2.1 from CIBSE (2006).

$$t_o = At_a + (1 - A)t_{mr} \tag{2.1}$$

Where:

t_o is the operative temperature

t_a is the air temperature

t_{mr} is the mean radiant temperature

A is a coefficient that depends on the air velocity v (ms^{-1})

For: $v < 0.2$: $A = 0.5$

For: $0.2 < v < 0.6$: $A = 0.6$

For: $0.6 < v < 1$: $A = 0.7$

Therefore at low air velocity (<0.2 ms^{-1}) the operative temperature may be taken as the average of the mean radiant temperature and air temperature.

In the case of free running dwellings, operative temperatures of 25 °C for living areas and 23 °C for bedrooms are found to be acceptable summer indoor comfort temperatures. CIBSE recommend that the peak temperatures should not exceed these comfort temperatures by more than 3 K, which produces a 28 °C upper threshold operative temperature for living areas and 26 °C for bedrooms. CIBSE Guide A states that "Thermal discomfort and quality of sleep begin to decrease if the bedroom temperature rises much above 24 °C" (CIBSE, 2006 1.6.4.3). Above 24 °C the occupants will be sleeping under a single sheet and will have exhausted their adaptive options. CIBSE recommends that the overheating thresholds should not be exceeded for more than 1% of occupied hours, which for housebound residents (the infirm or elderly) could be as many as 88 hours per year. The CIBSE guidance does not set a peak acceptable temperature for dwellings, but does state that operative temperatures above 30 °C are rarely acceptable in office buildings in the UK.

The main limitation with the hours over threshold temperature approach adopted in the CIBSE guidance is the inability to distinguish between two situations where the threshold has been exceeded. For example, given two cases where the threshold was exceeded for the same duration, but in case (a) the threshold was exceeded by 1 °C and in case (b) by 5 °C, both cases would record the same degree of overheating. However, case (b) would pose a much greater problem for comfort and health.

CIBSE set up an overheating task force in 2007 with the aim of reviewing the current approach to overheating in buildings, using adaptive thermal comfort criteria. The task force has yet to publish its recommendations, but has to date released two publications with guidance for improving summer thermal comfort (CIBSE, 2010a,b).

2.3.4 Adaptive threshold temperatures

The adaptive approach to thermal comfort thresholds is based on field research that suggests that people will adapt over time as the outdoor temperature rises and they will therefore become thermally comfortable at higher indoor temperatures. This is only the case for free running buildings, where occupants have some control over their indoor environment. The CIBSE 26 °C and 28 °C threshold temperatures for overheating (Section 2.3.3) already include some element of adaptive comfort because they are warm weather threshold temperatures derived for the UK, though as the climate warms these thresholds may increase.

British Standard EN 15251 (BSI, 2008) presents adaptive comfort temperatures for free running naturally ventilated buildings based on the running mean of the outdoor temperature (Figure 2.9). There are 3 categories depending on building type and/or occupants: (i) High, for the elderly, young, handicapped or infirm where the temperature can be ± 2K from the adaptive comfort temperature, (ii) Normal, for new buildings or renovations where the temperature range is ± 3K and (iii) Acceptable, for existing buildings, which may be ± 4K. These temperature limits are primarily based on studies using office buildings, but the Standard suggests that they may be applied to other comparable buildings, including residential. However,

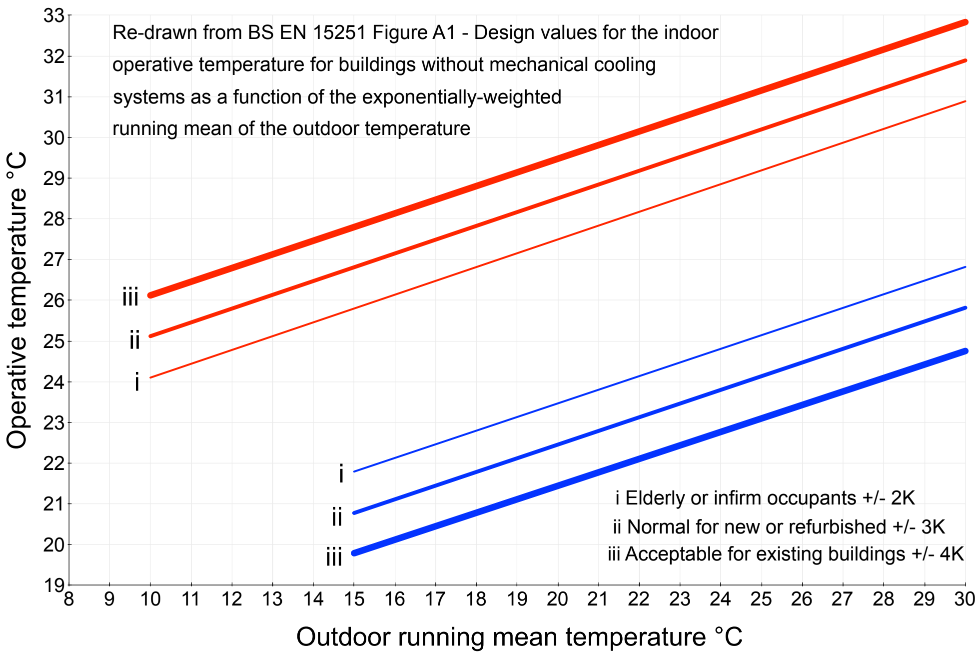

Figure 2.9 – Adaptive indoor design temperatures for free running buildings

there is no reference to how they may be applied for the lower comfort temperatures required in bedrooms at night time.

The outdoor running mean temperature is calculated using Equation 2.2. This value can then be used in Equations 2.3 and 2.4 to produce the lines in Figure 2.9 (equations from BSI, 2008).

$$\Theta_{rm} = 0.2\Theta_{ed-1} + 0.8\Theta_{rm-1} \tag{2.2}$$

Where:

Θ_{rm} = Running mean temperature for today

$\Theta_{\mathrm{rm-1}}$ = Running mean temperature for previous day

$\Theta_{\mathrm{ed-1}}$= Daily mean temperature for previous day

$$\text{Upper limit :} \qquad \Theta_{t\,max} = 0.33\Theta_{rm} + 18.8 + \mathrm{X} \tag{2.3}$$

$$\text{Lower limit :} \qquad \Theta_{t\,min} = 0.33\Theta_{rm} + 18.8 - \mathrm{X} \tag{2.4}$$

Where:

Θ_{t}= limit value of indoor operative temperature, °C

X = 2 for category i, 3 for category ii and 4 for category iii

CIBSE (2006) suggest adaptive threshold temperatures for free running office buildings that equate to category (i) in Equations 2.3 and 2.4, i.e. X = 2.

During both the 1976 and 2003 heat waves in London the outdoor running mean temperature slightly exceeded 25 °C, which would mean that, for healthy adults in existing buildings (category iii), the upper limit operative temperature would be 31 °C. This exceeds the current CIBSE guideline peak temperature (30 °C) for office spaces (CIBSE, 2006). BSI (2008) also notes that its graphs are based on a limited database for outdoor running mean temperatures above 25 °C.

There is also the issue of residents that spend their daytime hours in air conditioned cars on their way to air conditioned offices, before returning to their naturally ventilated houses in the evening. Less exposure to the higher outdoor temperatures could mean that they are less adapted and will have lower threshold comfort temperatures than people who do not spend time in conditioned environments.

Holmes and Hacker (2007) took some of the case study buildings from CIBSE (2005) and used the adaptive threshold temperatures from CIBSE (2006) to determine the amount of overheating for a naturally ventilated school and a mixed mode office. Both of these buildings have daytime only occupancy, where the fixed upper threshold temperature would have been 28 °C using the non adaptive method. None of the dwellings from CIBSE (2005) were assessed using the adaptive approach.

2.4 Quantifying overheating

Section 2.3.3 discussed the limitations of the current CIBSE overheating guidance, based on a simple percentage of occupied hours over threshold temperatures. The severity of the overheating is not captured by this method and furthermore this metric is designed to be used to quantify overheating over a whole year or summer. Section 2.3.4 also highlighted issues with using adaptive thresholds in dwellings, particularly for bedroom occupied periods. A recent book by Nicol et al. (2012) states that: "Future standards will need to provide a definition of overheating which, while not complete, will at least overcome the shortcomings of the 'over hours' model".

2.4.1 Degree hours

A method used by Orme and Palmer (2003) and the EST (2005) was to present the overheating in terms of the number of degree hours over threshold temperatures. Each degree centigrade over the threshold for one hour counts as 1 degree hour. Therefore, if the bedroom temperature reached 30 °C for 2 hours a total of 8 degree hours would be recorded (assuming the CIBSE comfort threshold of 26 °C). The number of degree hours arguably gives a better representation of the severity of the overheating problem than simply recording hours over the threshold temperature by quantifying the extent to which the threshold has been exceeded.

A further extension of the degree hour approach could be to use weighted degree hours, where the overheating rises exponentially above the threshold temperature. However, for this research it was decided that the simpler degree hour approach would allow comparison of the interventions and would be easier to understand for the project stakeholders.

2.5 Housing stock

It has been estimated that around 70% of the dwellings in use in the 2050s have already been built (Boardman et al., 2005). However, since that report was published in 2005 the UK has been experiencing a severe economic downturn, which has seen housing new build rates decline sharply. UK Government statistics show that new build completions dropped from 207,000 in 2007-08 to 128,000 in 2009-10 (CLG, 2010). With an increasing population and a shortage of new housing, the number of existing dwellings that will still be in use later this century is therefore likely to be higher than previously predicted. In order to meet carbon emissions targets, and to provide safe and comfortable homes in a changing climate, much of the current housing stock will therefore have to be refurbished and adapted.

2.5.1 Vulnerability of housing to overheating

Some types of dwellings are more susceptible to overheating than others. Older solid wall properties tend to have exposed thermal mass, lower airtightness and higher ceilings, allowing some stratification of warm air. Newer buildings on the other hand have higher standards of airtightness and are better insulated. Concerns about overheating in modern dwellings led to the publication of design guidance (Orme and Palmer, 2003), which stresses the importance of coupling thermal mass and night ventilation and reducing solar and casual gains in new house designs. The risks of overheating for advanced modern dwellings are also recognised in the Passivhaus design guidance (BRE, 2011a). Passivhaus dwellings are particularly sensitive to solar and casual gains due to their high levels of insulation and airtightness. Glazing is designed to be south facing to take advantage of solar gains in the winter, but with fixed shading to reduce solar gains from the higher altitude sun during the summer. Internal gains in Passivhaus dwellings are minimised by the use of low energy lighting and appliances.

Analysis of figures from previous heat waves in Paris (Vandentorren et al., 2006) and Chicago (Semenza et al., 1996) shows that living in top floor flats results in a significantly increased risk of mortality during heat waves. Attic flats with bedrooms under poorly insulated roofs were identified as particularly dangerous dwelling types in the Paris heat wave study. Peak temperatures recorded in UK dwellings during the 2003 heat wave (Wright et al., 2005) also identify flats as being particularly vulnerable to overheating. One of the London flats in the survey recorded internal temperatures of up to 39.2 °C, though it is not stated on which storey in the block this flat is located. The National Health Service (2011) also identifies living in top floor flats (particularly south-facing ones) as a high risk factor in the Heat Wave Plan for England. Chapter 6 presents the simulation results for the base case dwellings modelled in this research, comparing the overheating vulnerability of different built forms and building orientations.

2.5.2 English House Condition Survey (EHCS)

From 2002 to 2008 the Department for Communities and Local Government (CLG) published the English House Condition Survey (EHCS), which has since been merged with the Survey of English Housing to form the English Housing Survey (EHS). The full reports are usually published, with accompanying data sets, two years after the survey period. The latest available full report and data set (at the time of writing) was published in October 2010 and is based on the 2008 survey data (Department for Communities and Local Government, 2010). However, at the time when the housing research for this project was undertaken (during 2009), the latest available survey used the 2007 data set (Department for Communities and Local Government, 2009a) and was released under the EHCS heading.

The EHS and EHCS reports provide summary statistics on a range of housing details, including age, built form and energy efficiency upgrades (insulation and glazing).

However, to link these details to dwellings of a particular type and age within a region required analysis of the raw survey data. The EHCS Public Datasets are available on CD from CLG and the dataset for the 2007 survey was obtained (Department for Communities and Local Government, 2009b). The application of this data to select suitable dwellings for use in the simulations is addressed in Chapter 3.

2.6 Occupancy

The times at which occupants are inside their dwellings has a significant impact on their exposure to overheating, with the hottest periods occurring in the afternoon during a heat wave period. Different types of occupants will occupy the dwellings at different times of the day and one of the aims of the research was to assess the impact of dwelling occupancy on overheating exposure for different types of residents. Analysis of previous published reports and papers revealed the use of a wide range of occupancy profiles. A paper by Capon and Hacker (2009), which provided the methodology used for the report *Your home in a changing climate* (Arup, 2008) assumed occupancy by adults and young children for the case study house, with partial daytime occupancy and full evening and weekend occupancy. A flat and block of flats were also modelled and assumed to be occupied by two adults, with no daytime occupancy except at weekends. However, no detailed schedules or source of the assumptions is provided. The case studies presented in CIBSE (2005) again used assumed occupancy profiles based on dwelling type, but without any detailed information regarding occupied periods. Research by Hacker et al. (2008) provides more detailed occupancy profiles for a case study dwelling, again assuming family occupancy. The house is occupied all the time with one adult at work from 0800 to 1800. Bedroom hours are assumed to be 2300 to 0700 for adults and 2000 to 0700 for children, but in common with other research and reports the source of the assumptions is not stated.

In 1990 the Building Research Establishment (BRE) produced a research report with plans, construction and occupancy details for use in modelling (Allen and Pinney, 1990). Tables in the report give occupied periods for each room in the dwellings for two occupancy profiles: A *heavy* occupancy profile (a couple with 2 children under 5 and the wife not working) and a *light* profile (2 working adults and school age children). The profiles are based on previous work at BRE from 1980, which is no longer available. It is interesting to note that the children's bedroom occupied periods do not start until 2100. In 1980, when the occupancy research was undertaken, personal computers were rare and games consoles and televisions in children's rooms would have been less common than today. A recent study by Ofcom (2010) reported that two thirds of 8-11 year olds and three-quarters of 12-15 year olds now have a television in their bedroom, with similar proportions also having a games console in their bedroom.

Also absent in any of the reviewed publications was any distinction between different ages of residents and how this may affect, for example, sleeping patterns and hence bedroom occupied periods. The elderly are one of the vulnerable groups at significant risk during heat waves (Section 2.3.2) and as a sector of the population they have not been considered separately in previous research.

2.6.1 Time use survey

In 2000 the Office for National Statistics (ONS) conducted a detailed survey into occupant behaviour, the United Kingdom Time Use Survey (Office for National Statistics, 2003), which recorded the time spent by a sample of the UK population on different activities. The survey consisted of household questionnaires and 11,664 self-completed diaries. Types of activities and locations were recorded at 10 minute intervals for household occupants aged over 8 years old. Richardson et al. (2008) used the time use diary data to develop a stochastic occupancy model for energy demand simulations, producing a downloadable Excel workbook to generate representative active occupancy patterns. However, the profiles generated by the workbook do not distinguish between types of occupants (adults, children or elderly) or the time of year. The Time Use Survey data was used to derive occupancy profiles for this research, which is detailed in Section 3.5.1.

2.7 Dynamic thermal modelling

The use of software in building design is expanding as processing power increases and the costs reduce. A large range of software tools, of varying degrees of sophistication, is available for predicting the performance of buildings. At one end of the scale are simple steady state tools for energy use calculation, such as SBEM (Simplified Building Energy Model), developed by the BRE for non-domestic buildings (BRE, 2011b). However, such tools do not calculate internal temperatures and should not be used for design purposes. At the other end of the spectrum are comprehensive Dynamic Thermal Modelling (DTM) software packages, which enable accurate analysis of building performance.

DTM uses hourly data for external weather conditions along with hourly or sub-hourly data regarding building inputs, such as internal gains and ventilation. An iterative calculation process then predicts the gains and losses through conduction, convection and radiation for the detailed building model. A large range of outputs can be selected, from hourly zone temperatures and comfort predictions to annual energy consumption and CO_2 emissions.

Although DTM software is more commonly used in larger commercial design projects it can equally be used in dwelling design and for predicting the effect of interventions on existing dwellings. Several commercial software packages are available, for example Integrated Environmental Solutions Virtual Environment (IES, 2011b), which uses proprietary calculation engines and is configured for ease of use and consistency in the building design process. However, researchers often need to adapt and control simulation software in ways that are not easily achieved when using commercial 'black box' simulation tools. Some of the larger building consultancy firms have produced their own in-house DTM software packages, which are not available for general use. Arup's ENERGY2 software was used by Hacker et al. (2008) and Holmes and Hacker (2007) and was also the software used by Arup researchers to produce the simulation results in CIBSE Report TM36 (CIBSE, 2005).

One of the more popular research DTM tools is ESPr, developed by the Energy Systems Research Unit (ESRU) at the University of Strathclyde (ESRU, 2011). It is available under an open source licence and was used in research into overheating by Jenkins et al. (2009a) and Peacock et al. (2010). One of the limitations of ESPr is the lack of a fully integrated front-end to input building geometry and construction details, it also has limited databases compared to commercial software. It is not very intuitive to use and, as noted in the ESPr software overview (ESRU, 2011), is better learned via a mentor than by self-instruction.

EnergyPlus is another freely available [2] DTM software tool, developed by the U.S. Department of Energy (2010). The main advantage of EnergyPlus over other open source tools is the availability of user-friendly front-end interfaces such as DesignBuilder (2011), which allows easy construction of building geometry and input of materials, gains and schedules. The EnergyPlus input data file (IDF) can then be exported for use in large scale parametric simulations. DesignBuilder and EnergyPlus were chosen as the DTM simulation tools for this research and are discussed in detail in Chapter 5.

[2] Although free to download, alteration of the source code is restricted to licensed developers

2.8 Weather files

The aim of the research was to predict the effectiveness of a range of interventions for reducing overheating during heat waves. Simulation weather data was therefore required that contained heat wave periods. Previously published guidance and research has used a variety of approaches when selecting weather data for use in simulations. CIBSE Report TM36 CIBSE (2005), along with the Three Regions Climate Change Group publication Your Home in a Changing Climate (Arup, 2008), used future morphed weather data based on the UKCIP02 climate projections (Hulme et al., 2002). The Energy Saving Trust guide to reducing overheating (EST, 2005) chose to use the current CIBSE Design Summer Year (DSY) simulation weather file for London and research by Gaterell and McEvoy (2005) and de Wilde et al. (2008) used Southern European weather as a proxy for UK weather later this century.

2.8.1 Design Summer Year

CIBSE weather files are widely used by designers in the UK to predict building performance. Two types of weather file are provided for each location: the Test Reference Year (TRY) and the Design Summer Year (DSY). The TRY is constructed from individual 'typical' months from a 20 year period, generally falling between 1983 and 2004, and is used to predict building energy use over a year. The DSY is one of the years from the 20 year dataset, selected to be the mid year of the upper quartile. The DSY files allow designers to assess the likelihood of a building overheating in a warm, but not extreme, summer.

2.8.2 Future morphed weather

Following the publication of the UK climate projections in UKCIP02 (Hulme et al., 2002), Belcher et al. (2005) produced a set of weather files using a procedure they termed morphing. This involved taking current CIBSE TRY and DSY weather files and applying change factors to lift or stretch weather variables. This produced simulation weather files representative of UK weather for future time periods (2020s, 2050s, 2080s), assuming four different CO_2 emission scenarios (low, medium, medium-high, high). However, because the weather files are based on existing TRY and DSY files they do not contain extreme heat wave periods.

Consequently, in order to find suitable heat wave periods approaching the severity of real heat waves experienced in recent years, it was necessary to use future predicted weather files for periods towards the end of the century (2080s).

During the course of this research DEFRA and the UKCIP released the updated UKCP09 projections (see Section 2.2.3). The latest projections (Murphy et al., 2009) were released along with an online Weather Generator tool, since updated in February 2011 (DEFRA, 2011). However, spells of similar weather patterns, such as those that constitute heat wave events, are difficult to reproduce using the Weather Generator, with the most extreme events not being simulated very well (Jones et al., 2010). There have been recent advances in producing future probabilistic weather files, but there is still no consensus on their suitability, particularly for investigating heat wave periods.

2.8.3 Southern European weather

Depending on which emissions scenario is considered, there are a variety of Southern European locations that currently experience climates similar to that expected in the UK later this century. For example, Gaterell and McEvoy (2005) used Milan to represent the UK in the 2050s under a low emissions scenario (UKCIP02) and Rome for the 2050s assuming a high emissions scenario. The main problem with this approach is the different latitude of Southern European locations compared to the

UK, which would have a large impact on solar shading calculations. Other weather variables, for example wind speed and humidity, may also be very different.

2.8.4 Real heat wave years

Using simulation weather files generated from years that contained real heat waves allows analysis of the dwellings and the effect of interventions during known extreme weather events for the particular location. Section 2.2 discussed the most extreme heat waves to hit the UK in the last 35 years, notably 1976, 1995, 2003 and 2006. The most famous and widely quoted of these was the Europe-wide heat wave during August 2003.

Of the options considered for weather data, this was the only one that could provide extreme heat wave periods for simulation and was the approach adopted for this research. Relating simulation results to known extreme weather events was also of benefit when disseminating the research to stakeholders, who could relate to these recent heat waves more readily than predicted future weather events. Construction of the 2003 simulation weather file is discussed in Section 5.5 and Appendix D.

2.9 Research and guidance on overheating in dwellings

Typical UK houses have little or no external solar shading, unless provided by neighbouring buildings or trees. They also usually have relatively dark coloured walls and roofs, which absorb solar radiation. Closed room layouts make cross ventilation difficult to achieve in many cases, particularly in apartments that occupy one side of a building. The range of passive interventions that can be applied to reduce overheating in dwellings includes behavioural changes along with physical additions or alterations to the building fabric. Adaptations can also include changes to the environment surrounding the building, such as planting shade trees or changing the albedo of roads and pavements to reduce the ambient air temperature.

In 2002 the UK Climate Impacts Programme published the UKCIP02 Climate Projections (Hulme et al., 2002), which predicted future increases in extreme weather events due to climate change and the following year the problem of overheating in dwellings was brought into sharp focus by the increased mortality observed during the 2003 heat wave. The need for detailed information and advice on overheating was recognised by various institutions, the government and the research community.

Some of the identified research has looked at single interventions, such as ventilation strategies or solar coatings and these are discussed in context in Chapter 4. This section reviews research that focusses on overheating reduction for dwellings by combining adaptation measures. Some of the research has been used to produce guidance aimed at designers, decision makers and building users and these publications are also discussed. Some are technical, quantifying the effect of interventions, whilst others offer more general advice and information.

In response to more stringent Building Regulations, demanding higher levels of insulation in new dwellings, Orme et al. (2003) used dynamic thermal modelling (IES, 2011b) to assess the overheating performance of selected dwelling types. The simulations were used to identify key parameters that lead to overheating and to propose design options to limit the problem. The research was aimed at producing design guidance for the construction industry (the research was conducted at Faber Maunsell) and therefore the construction methods were limited to new dwellings (with low U-values). Four key dwelling characteristics were identified that influence overheating: thermal mass, solar gain, ventilation and incidental gains. Some of the proposed design modifications, such as increasing the roof albedo or adding window shading, could be applied to retrofits. Employing a high mass design (with a suitable ventilation strategy) was one of the most effective solutions, but this would need to be incorporated at the design stage and is not usually a retrofit solution. Their research used the degree hour method to quantify whole summer overheating (Section 2.4.1) and showed that overheating could be reduced by almost 80% using a combination of high thermal mass, night ventilation, solar shading, reduced gains and high roof albedo.

Orme and Palmer (2003) modelled the effect of fitting external louvres to the windows of a modern semi-detached house of lightweight construction, combined with a night ventilation strategy. Their simulation results predict that overheating degree hours would be reduced by between 50% and 60%. Their research also estimates the effect of curtains to be a reduction of 10% - 15% in solar gains.

Coley et al. (2012) modelled a range of physical and behavioural interventions for a lightweight house in London. The physical changes involved increasing the thermal mass, fitting fixed shading and solar control glazing. Behavioural interventions included night ventilation, modified window opening and reducing internal gains. The house was modelled for the current climate and 3 variants of the 2050s climate using UKCP09 probabilistic weather data. The results demonstrate the ability of behavioural interventions to compensate for uncertainties in future climate scenarios.

2.9.1 ARCC research projects

In 2007 the UK Engineering and Physical Sciences Research Council (EPSRC) provided funding for 14 research projects to address climate change adaptation in the built environment, including the CREW project (Community Resilience to Extreme Weather) to which this research is linked (CREW, 2011). In 2009 the ARCC (Adaptation and Resilience in a Changing Climate) network was established to coordinate the 14 EPSRC projects (ARCC, 2012).

There are overlaps between some of the ARCC projects, with three looking at different ways of using the UKCP09 climate projections to produce future probabilistic weather files for use in building simulation. Others are investigating flooding, transport and infrastructure impacts due to climate change. Due to the staggered start dates, several of the projects have yet to publish their main research outputs. Some of the projects have research aims and outputs relevant to the research presented in this thesis. The following section provides a brief description of the projects that directly address dwelling overheating (see ARCC, 2012 for links to the projects):

- CREW - Community Resilience to Extreme Weather (2008 - 2011)
  The CREW project consists of 6 programme packages (PP1-6) spread across 14 universities. PP1 involved the investigation and assessment of coping methods to deal with extreme weather events. The research presented in this thesis constitutes the PP1 output for the project, which was used to inform a retrofit decision making framework (PP2) and produce prototype web tools (PP5). Other programme packages investigated socio-economic factors (PP3) and severe weather events risk and vulnerability (PP4), with PP6 being project management.

- SCORCHIO - Sustainable Cities: Options for Responding to Climate Change Impacts and Outcomes (2007 - 2010)
  This project investigated the urban heat island effect for the cities of Manchester (Smith et al., 2009) and Sheffield (Lee and Sharples, 2008). The project included DTM modelling (DesignBuilder) of adaptation measures in buildings and the output was used in the development of a prototype GIS mapping based decision support tool for climate adaptation. The dwelling modelling included the effects of orientation, glazing, insulation and internal and external shading for future climate scenarios in Manchester and Sheffield, but the simulation work has not been separately published.

- LUCID - The development of a Local Urban Climate model and its application to the Intelligent Development of cities (2007 - 2010)

This project investigated the impact of climate change and the urban heat island effect on the local urban climate. The research used steady-state modelling to predict future annual energy use, whilst increased mortality due to higher temperatures was predicted from the relationship between mortality and outdoor temperature (Mavrogianni et al., 2009). A free-running office building was also simulated using DTM software (EnergyPlus) in selected locations within the London urban heat island (Mavrogianni et al., 2011). Overheating in dwellings has been modelled, also using EnergyPlus (Mavrogianni et al., 2012). In this case GIS mapping was used to identify 15 dwelling archetypes, from which 27 variants were simulated using current (CIBSE DSY) and future (UKCP09 probabilistic) weather data. The modelling assumed all dwellings built before 1960 were of solid wall construction, although many dwellings constructed since the 1930s have cavity walls. The final wall U-values for pre-1980 dwellings after the addition of internal wall insulation was modelled at 0.60 W/m^{2}K, higher than current Building Regulations U-value of 0.30 W/m^{2}K for upgrades to existing walls (HM Government, 2010a). A parametric study, totalling 3,456 simulations, modelled the effect of insulation and glazing upgrades, but did not include solar control interventions or modifications to ventilation strategies. Also, different occupancy patterns were not considered and windows were assumed to be closed at night. The results indicated broadly that a combination of insulation and glazing upgrades reduced overheating, but internal wall insulation alone tended to increase overheating in many cases.

- SNACC - Suburban Neighbourhood Adaptation for a Changing Climate (2009 - 2012)

  The SNACC project is primarily focussed on neighbourhood level adaptation and mitigation. To date different types of modelling approaches have been used to assess climate change impacts, including DTM simulation of adaptation measures for dwellings using IES software. Gupta and Gregg (2012) used UKCP09 probabilistic weather data to model the effect of interventions assuming the 90th percentile of the high emissions scenario (i.e. worst case) for the 2030s, 2050s and 2080s. Six 'retrofit packages', which include insulation, glazing and solar control, but excluding ventilation measures, were modelled using 4 dwelling types, each using the same construction methods, but of different built form. The results are presented in terms of occupied hours above CIBSE threshold temperatures and include analysis of the effect on heating energy use.

2.9.2 CIBSE: Technical Report TM36

In 2005 the Chartered Institution of Building Services Engineers (CIBSE) published its technical report TM36: Climate change and the indoor environment: Impacts and adaptation.(CIBSE, 2005), which was co-funded by Arup and the Department of Trade and Industry. It is widely referenced and provides a good background to the issues surrounding climate change adaptation. Case studies are presented for a variety of buildings including offices, schools and dwellings, using dynamic thermal simulation to assess their performance through to the 2080s. Future climates are represented in the simulations by the use of 'morphed' weather files (see Section 2.8) based on the UKCIP02 climate projections (Hulme et al., 2002). The software employed to carry out the dynamic thermal simulations (ENERGY2) was developed in-house by Arup and is not commercially available.

The report identifies four principles for adapting to overheating: 'switch off', 'absorb', 'blow away' and 'cool'. Switch off refers to reducing gains, in this case by limiting solar gain through windows by using blinds or shutters. Absorb utilises thermal mass, which is assessed by comparing the same building with low and high mass construction, and therefore not strictly an adaptation option for retrofit[3]. Blow away refers to intelligent ventilation strategies, such as preventing windows opening in hot weather and using night ventilation to restore coolth in the building fabric. The last principle, cool, is the installation of mechanical cooling systems, which may be inevitable for some building types under future climates, even if other adaptation measures are undertaken.

The report uses CIBSE comfort threshold temperatures to define the point above which overheating occurs, citing 28 °C as the threshold for living rooms and 25 °C for bedrooms, though CIBSE guide A (CIBSE, 2006) sets the thresholds at 28 °C and 26 °C respectively. The effect of a limited range of interventions is considered for dwellings, including external shading by shutters or blinds, reduced ventilation during warm periods, night ventilation and the effect of different levels of thermal mass in otherwise identical buildings. Combined interventions are modelled and the results presented as reductions in the percentage of occupied hours over the comfort threshold temperatures for the adapted buildings compared to the base case buildings. TM36 does not consider the effects of individual interventions with the exception of a limited analysis of the effects of solar shading and ventilation coupled to thermal mass for two variants of one of the dwellings (low and high mass constructions). The report also acknowledges that some adaptations have not been considered in detail, such as airtightness and insulation.

TM36 does not consider different occupancy profiles within the same dwelling type and only provides results for one dwelling orientation in each case. A reduced version of TM36; Beating the Heat: keeping UK buildings cool in a warming climate (Hacker et al., 2005) contains the key messages from TM36 for wider circulation in an accessible format.

[3]Although the effect of adding thermal mass could be achieved by installing phase change materials they were not considered in this research. Their possible use is discussed in Chapter 9.

Research by Hacker and Holmes (2007) and Holmes and Hacker (2007) contains background to the simulation modelling results in TM36, including some of the case study buildings, although none of the dwellings are featured in these publications.

2.9.3 Your home in a changing climate

Arup also produced a report for The Three Regions Climate Change Group (Arup, 2008), which provides advice for policymakers, housing professionals and householders in London, East England and South East England. The report provides retrofit guidance to improve resilience to flooding, water stress and overheating in a changing climate and argues that adaptation should be considered during normal refurbishment cycles. The study uses the UKCIP02 (Hulme et al., 2002) climate projections and contrasts the benefits and limitations of a range of adaptations, including approximate costs. Case study houses are modelled for family occupancy and, in common with CIBSE TM36, the effects of combined interventions are presented as the reduction in percentage of occupied hours over CIBSE comfort threshold temperatures (in this case 28 °C for living rooms and 26 °C for bedrooms). The report also shows the reduction in cooling degree hours for a summer month that may be expected for the adapted dwellings. Comparison of different dwelling orientations and occupancy profiles were not considered in the report. A conference paper by Capon and Hacker (2009) contains some of the background to the modelling assumptions and methodology used to produce the report, including some of the cost assumptions.

2.9.4 Energy Saving Trust CE129

In 2005 the Energy Saving Trust published CE129: Reducing overheating - a designer's guide (EST, 2005) as part of its Energy Efficiency Best Practice in Housing series. The technical information within the guide was provided by the Building

Research Establishment (BRE). As the title suggests, the guide is aimed at house designers and many of the suggested measures would have to be considered at the design stage, such as heavier weight construction or choice of building orientation. However, the guide still suggests some interventions suitable for retrofitting, such as external shading and modified ventilation.

The performance of the design options and interventions was modelled using IES-VE DTM software (IES, 2011b). The overheating assessment was not based on future climate projections, it used the current CIBSE design summer year (DSY) weather file for London (see Section 2.8), which does not contain any extreme (heat wave) periods. The results are presented as the number of degree hours over a threshold temperature of 27 °C for the whole summer for single design options/interventions based on one house type (semi-detached). The guide is limited to this one house type and does not compare overheating for different occupancy profiles or for the full range of dwelling orientations.

2.9.5 CIBSE Knowledge Series: KS16

CIBSE set up an overheating task force in 2007, which has to date released two publications: a short information leaflet (CIBSE, 2010b) and a more comprehensive guide as part of its Knowledge Series, *How to manage overheating in buildings: KS16* (CIBSE, 2010a). The main aim of the task force is to develop the use of adaptive comfort threshold temperatures and KS16 uses the adaptive thresholds derived from BS EN15251:2007 (BSI, 2008) to define overheating. CIBSE KS16 is aimed at building owners, managers and users (i.e. non-technical) and provides a good background to the reasons why buildings overheat. It goes on to provide practical advice for reducing overheating, suggesting both building adaptations and occupant behaviour changes.

2.9.6 Heat wave plan for England

In response to the 2003 heat wave, which had severe consequences for the National Health Service, a Heat Wave Plan for England was published and is regularly updated (National Health Service, 2011). The advice contained in the Plan is very general and contains suggested behavioural modifications, such as loose clothing, cold drinks and avoiding direct sun. The Plan does contain some (unquantified) advice for building adaptation, including keeping windows shut during the hotter parts of the day, fitting external shading, coating external surfaces with reflective paints, reducing internal gains by switching off equipment and insulating lofts and cavity walls.

2.9.7 London specific guidance

The recently published Climate Change Adaptation Strategy for London (Greater London Authority, 2011) includes information and advice tailored for the Greater London area, accounting for the problems associated with living within an urban heat island. The report references some of the other guidance listed above and also encourages London's Registered Social Landlords to use the retrofit toolkit developed during this research (Section 7.4).

The City of London published its own climate adaptation strategy (Acclimatise, 2010), which also provides information about the particular issues in London as a result of the heat island effect. Limited advice is provided for reducing overheating in buildings by using shutters or blinds and heavier weight constructions and for reducing the heat island effect through cool roofs, pavements and vegetation.

2.10 Space heating energy use in UK dwellings

The main focus of this research was to investigate the effect of interventions for reducing overheating during heat waves. During the early phase of the project initial simulation results for overheating reduction were presented to stakeholders and two main questions were posed: what would be the cost of the interventions? (see Section 4.8) and what would be the effect on annual energy use? It was acknowledged that retrofit decisions cannot be taken in isolation and it is important to know what effect any proposed changes or additions to dwellings will have on space heating energy use.

The energy used for space heating in UK housing varies enormously. A semi-detached house built in the 1900s, with no fabric upgrades, will use around 18,000 kWh per year compared to around 5,000 kWh per year for a similar house constructed to 2006 Building Regulations (Zero Carbon Hub, 2010).

Climate change is predicting warmer winters as well as hotter summers (Murphy et al., 2009), which will reduce future heating energy demand. Gupta and Gregg (2012) used dynamic thermal modelling to calculate heating energy consumption for a range of dwelling types for the current climate and for future climates using probabilistic weather files based on the latest UKCP09 projections. Their results predict reductions of 26-41% by the 2030s and 43-75% by the 2080s, depending on dwelling type and assuming the 90th percentile of the high emissions scenario (i.e. the most extreme projections). A modelling study by Collins et al. (2010) used the previous UKCIP02 high emissions scenario climate projections to predict a heating energy use reduction of 26% for the London area by the 2080s.

Simulation results in Gupta and Gregg (2012) show that wall insulation can reduce heating energy use in the current climate by up to 50% and that reducing the solar absorptivity of external surfaces would increase heating energy use by 2%. Gaterell and McEvoy (2005) found that adding cavity wall insulation to an uninsulated detached house would reduce heating energy use by 25%. Dynamic thermal modelling on cool coatings applied to roofs by Halewood and de Wilde (2008) showed an increase in heating energy use of about 3% when applied to the slates of a terraced house in Birmingham.

Winter cold is currently the major cause of temperature related mortality in the UK and dwelling retrofit decision making tied to government initiatives, such as the Green Deal (DECC, 2010b), will require thermal improvements linked to performance under current rather than future climates. Some interventions, such as increased insulation, will significantly reduce heating energy use, whilst solar control interventions may lead to increased energy use due to the loss of beneficial heat gains during the heating season.

When interventions are combined there will be compounded effects and in some cases trade-offs between reductions and increases in heating energy use. CIBSE (2005) contains some limited details for energy use post adaptation in office buildings and a school, but not for any of the modelled dwellings. Other guidance publications for overheating reduction do not consider the effect of interventions on heating energy use, which is addressed in this research. The methodology used to model space heating energy use is detailed in Section 5.6 and the effects of interventions on heating energy use are presented in Chapters 6-8.

2.11 Summary

This chapter has explored the background to the research project by looking at the definition of heat waves and identifying the overheating issues that they present. Thermal comfort has been discussed and the problems of using adaptive comfort thresholds for dwellings was identified. Housing stock and occupancy databases were introduced, identifying their usefulness for constructing the simulation models and settings, which will be addressed in Chapters 3 and 5.

A review of existing research and available guidance on overheating identified gaps in knowledge that this research seeks to address, notably:

- The lack of detailed quantitative information on the effect of single and combined interventions for overheating reduction.
- The lack of research assessing heating energy use effects of combined interventions.
- Consideration of different occupancy profiles and dwelling orientations.

The following chapters will discuss the modelling methodology before presenting and discussing the results of the simulations.

Chapter 3

Dwellings for modelling

3.1 Foreword

The previous chapter covered the background to the research and introduced the English House Condition Survey (EHCS) as a resource for determining detailed information about UK dwellings. The occupancy profiles used in previous research were also discussed and the lack of information regarding occupancy was highlighted.

This chapter shows how the EHCS (Department for Communities and Local Government, 2009a) and Time Use Survey (Office for National Statistics, 2003) datasets were used to select representative dwellings, construction details and occupancy profiles for use in the simulations. Other modelling assumptions, including infiltration and internal gains are also presented.

3.2 Dwelling selection

Southern England is the area of the UK predicted to be at greatest risk from future summertime overheating (Murphy et al., 2009). The CREW project selected five South London boroughs to be the target study area, which fall within this 'at risk' region. A method was required to identify representative dwellings for use in the research, which would span the range of construction methods and built forms found in the project study area. The 2009 English House Condition Survey (EHCS) (Department for Communities and Local Government, 2009a) provided a method of analysing the housing stock in London and South East England to determine the most common types of dwelling, their ages and other key construction details. Figure 3.1 shows the types of housing found within the combined region, broken down into age bands.

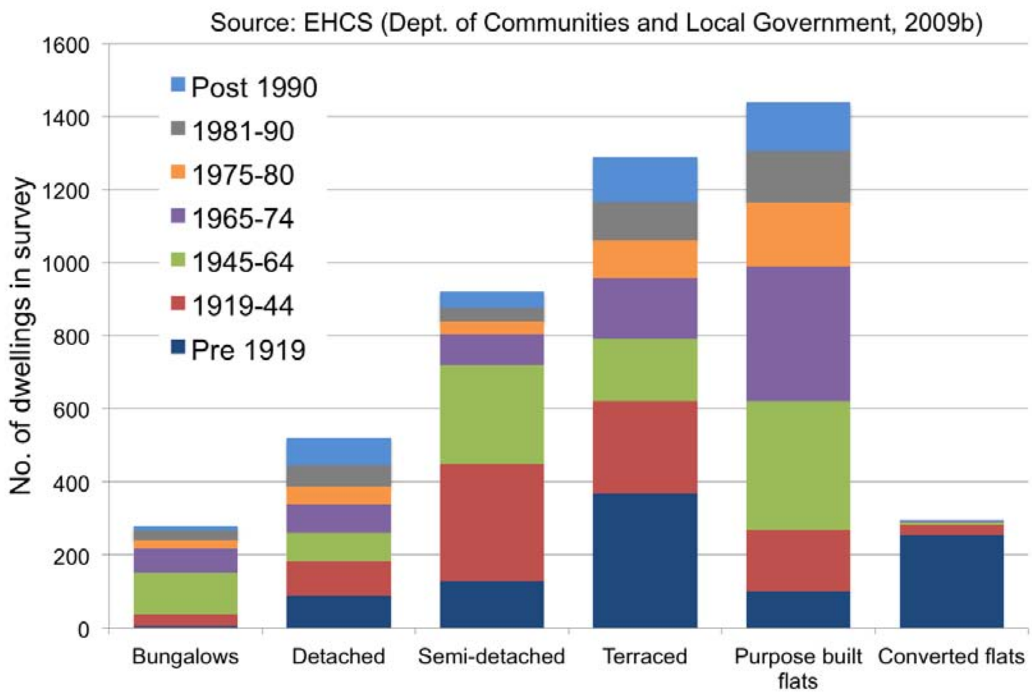

Figure 3.1 – Housing stock by type and age, London and South East England

The simulation processing time and the time taken to analyse the results had to be balanced against the desire to cover as many dwelling types as possible. It was decided that selecting four dwelling types would be sufficient to represent the range of dwellings, ages and construction methods, whilst still being manageable within the project timeframe. From Figure 3.1 it can be seen that the four most common dwelling types are purpose built flats, followed by terraced houses, semi-detached houses and detached houses. Bungalows and converted flats are the least common dwelling types. The total sample size in the 2009 EHCS data set for dwellings in London and South East England was 4,744.

The next step, having determined the four most common dwelling types, was to select age bands and construction properties for each one. There are certain key periods in housing where major changes in construction methods occurred. Up to around 1930 most houses were built with solid walls, but since then walls have been predominantly of cavity construction. The first Building Regulations were introduced in 1965 and a 1978 amendment saw the introduction of cavity wall insulation. The Building Act in 1984 saw further refinements to the Building Regulations, which have since undergone regular updates to improve thermal standards. Unfortunately, the age bands within the EHCS datasets do not follow these key periods rigidly. For example, there is one band covering the period 1919 to 1944, which will have a mixture of solid and cavity wall dwellings.

3.2.0.1 Terraced houses

Approximately 29% of the surveyed terraced houses were built before 1919 and around 20% were built between 1919 and 1944. The survey data shows that 51% of the terraced houses built during the 1919 to 1944 period have solid wall construction, therefore approximately 39% of the terraced houses in London and South East England will have solid wall construction. Uninsulated cavity wall construction can be attributed to most of the houses built between 1945 and 1974, which accounts for approximately 26% of the terraced housing stock. Houses built during the 1975 to 1980 period are likely to have some level of cavity wall insulation following the changes to Building Regulations in 1978. Houses constructed post 1980 are likely to have higher levels of cavity wall insulation, and account for approximately 18% of the terraced housing stock. The most common construction method for terraced housing is therefore likely to be uninsulated solid wall and it was decided that the solid wall construction method would be represented in the research by 19th century

(Victorian) terraced houses. Original construction was usually of 9" (0.215m) solid brick walls, with either slate or tiled roofs, single-glazed sash windows and no insulation. From the EHCS data it was determined that 56% of pre 1919 terraced houses in the London and South East England regions have more than 50% double-glazing installed. Of those properties with double-glazing, 83% have uPVC window frames. Levels of loft insulation vary, but the most common depth is between 100mm and 150mm, with an average depth across all pre 1919 terraced houses of 98mm, consistent with joist-level insulation (assuming 100mm joists). Average floor area is 94m^2, with 5 habitable rooms: living room; dining room; and 3 bedrooms (kitchens and bathrooms do not count as habitable rooms). Nineteenth century terraced houses were usually constructed without kitchens and bathrooms, but most have been extended at the rear during the 20th Century, converting the old lean-to sculleries into kitchens, with bathrooms above.

3.2.0.2 Semi-detached houses

There was an explosion of house building during the 1930s, with over 3 million homes constructed, most of which were semi-detached (Rock, 2005). The EHCS survey data (Figure 3.1) identifies the 1919 to 1944 period as the most common for semi-detached houses (35%), closely followed by the 1945 to 1964 period (29%). Semi-detached house building remained largely unchanged from the 1930s through to as late as the 1960s (Rock, 2005), with similar house layouts and construction methods. Houses built in the 1930s were therefore chosen to represent semi-detached type dwellings in the research. The survey shows that 73% of the semi-detached houses from the period have uninsulated cavity walls and 88% have greater than 50% double-glazing (57% have 100% double-glazing). Of those houses with double-glazing, 69% have uPVC as the window frame material. As with the terraced housing, the most common band for loft insulation depth is 100mm to 150mm, with an average thickness of 106mm, again consistent with joist level insulation. The average floor area is $95m^2$, with a living room, dining room, 3 bedrooms, kitchen and bathroom.

3.2.0.3 Flats

The construction of purpose built flats grew rapidly during the post war period 1945 to 1964, which accounts for 25% of purpose built flats in London and South East England. The following 10 years from 1965 to 1974 saw continued growth in flat construction, accounting for 26% of flats in the EHCS survey. Flats built in the 1960s were chosen to represent dwellings spanning these periods. Of the flats constructed between 1945 and 1974, 66% have cavity wall construction. Of those with cavity wall construction, 76% do not have any cavity insulation. The most common number of storeys is between 3 and 4, accounting for 44% of flats. Roof construction is fairly evenly split between tiled (49%) and flat roofs with an asphalt/felt covering (45%). It was decided that a flat roof construction with asphalt covering would be used in the simulation model. Tiled roofs are represented in the other dwelling types and this would allow assessment of the effect of flat roof construction on overheating exposure. Full double-glazing is fitted to 73% of the flats, with only 24% having single-glazing. The most common frame material for double-glazing is uPVC, found in 89% of cases. The average floor area for flats is $59m^2$, with two bedrooms, bathroom, kitchen and a living room with dining area.

3.2.0.4 Detached houses

Detached house construction increased during the 1965 to 1980 period to account for approximately 24% of detached housing stock. Construction since 1980 accounts for a slightly higher proportion at just over 25%. The Building Regulations have been changing at a rapid rate during these periods, making selection of representative insulation, glazing and other properties difficult. A decision was made to construct the detached house model to the latest Building Regulations in force at the time of simulation model construction (2009), which were the 2006 Regulations (Office of the Deputy Prime Minister, 2006b). This house type was chosen to demonstrate how a modern dwelling performs during a heat wave period. The average floor area for London and South East England detached houses built since 1990 is 145m^2, based on a sample of 73 houses in the survey.

3.3 Simulation models

No single resource for plans and construction details was available that covered the range of dwelling types selected for simulation. In 1990 the Building Research Establishment (BRE) produced a technical document containing dwelling plans for modelling (Allen and Pinney, 1990). However, this does not contain any plans for flats and the detached house chosen for analysis in this research was constructed to recent (much more stringent) building regulations than the one contained in the BRE document.

The following sections detail the sources for the simulation models and their construction methods and materials, including assumed upgrades to insulation and glazing derived from the EHCS dataset as discussed in Section 3.2.

A variety of sources were used to ensure that construction methods and materials for the models were representative of dwellings from the periods, including Chudley and Greeno (2010); Glover (2009); Jackson and Day (2002); Riley and Howard (2002); Allen and Pinney (1990) and Marshall and Worthing (2006). The detailed construction and glazing material properties are given in Appendix A.

3.3.1 Terraced houses

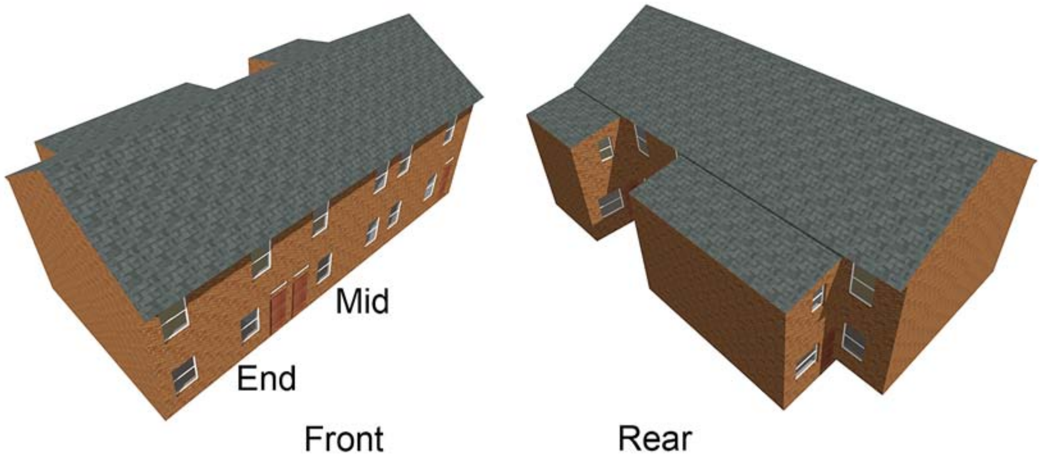

Figure 3.2 – Terraced houses model

The terraced house model (Figure 3.2) was constructed from site survey data obtained during an energy audit of a house in South East England. A short row of 3 terraced houses was constructed using DesignBuilder software. This allows comparison between an end-terraced house and mid-terraced house, the end-terraced house having much greater external wall area for the same floor and glazing area. The floor plans in Figure 3.3 show that the living rooms are at the front on the ground floor, whilst the main bedrooms are at the rear on the first floor. The floor area for each terraced house is 91m^2, very close to the average for pre 1919 terraced houses of 94m^2 from the EHCS data. The glazing dimensions (which include the frame area) are shown in Figure 3.4.

The houses are constructed from solid brick walls, with a suspended timber ground floor and a clay-tiled roof. The rear extension, containing the kitchen and bathroom, was added during the latter part of the 20th century. This would be a common addition to houses of the period and is constructed with uninsulated cavity walls and a solid concrete ground floor. The construction properties used in the model are summarised in Table 3.1.

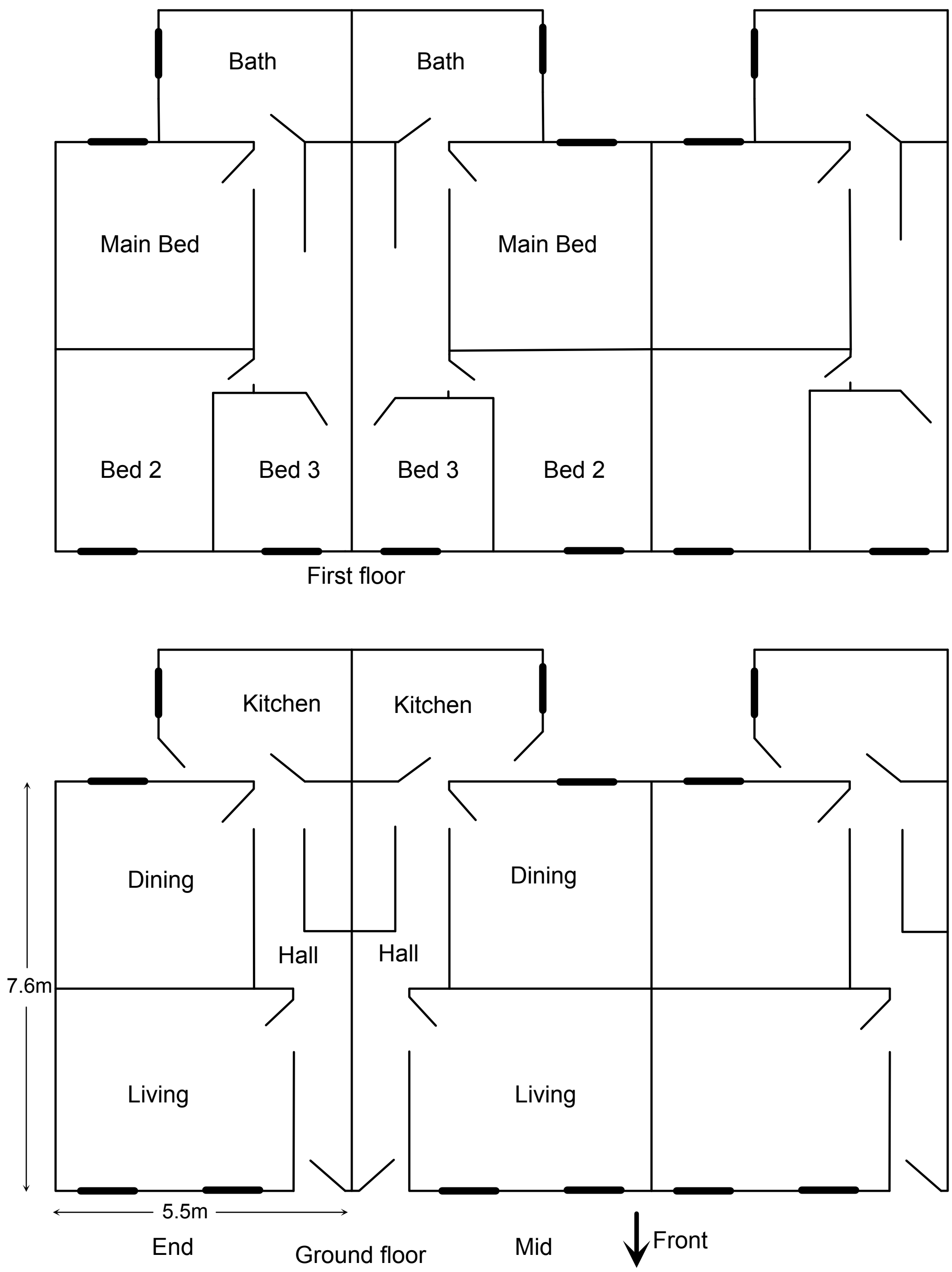

Figure 3.3 – Terraced house floor plans

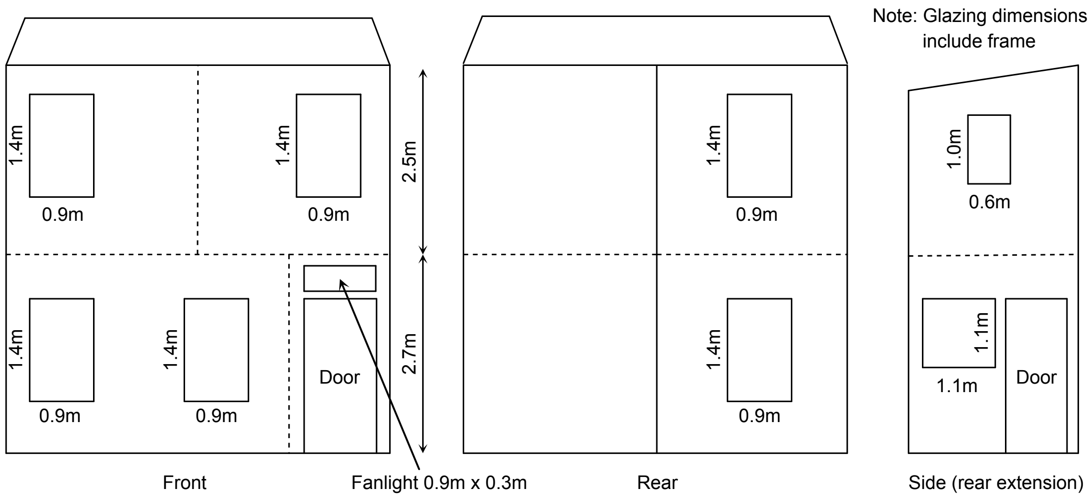

Figure 3.4 – Terraced house glazing (end-terraced shown)

	Construction	U-value W/m^2 K	Solar absorptivity
External walls (main house)	Solid brick (london stock) 0.215m with internal plaster 0.013m Total thickness 0.228m	2.12	0.6
External walls (rear extension)	Brick/block with 0.05m uninsulated cavity and internal plaster 0.013m Total thickness 0.268m	1.43	0.6
Roof	Clay tiles (dark) over roofing felt with 0.1m glass fibre joist level insulation	0.36	0.8
Ground floor (main house)	Suspended timber with underlay and carpet 0.3m cavity to clay	0.84	0.6
Ground floor (rear extension)	Cast concrete 0.1m over stone chippings to clay, uninsulated	1.25	0.6
First floor	Floorboards with carpet and underlay, air gap to plasterboard	1.02	0.6
Internal partitions	Single brick with plaster each side	1.69	0.5
Glazing	Pre-2002 double-glazing SHGC* 0.708	2.70	
Window frames	White uPVC	3.48	0.4
External doors	Wooden	2.25	0.5

*SHGC = Solar Heat Gain Coefficient - see Section 4.5.0.4

Table 3.1 – Terraced houses construction details

3.3.2 Semi-detached house

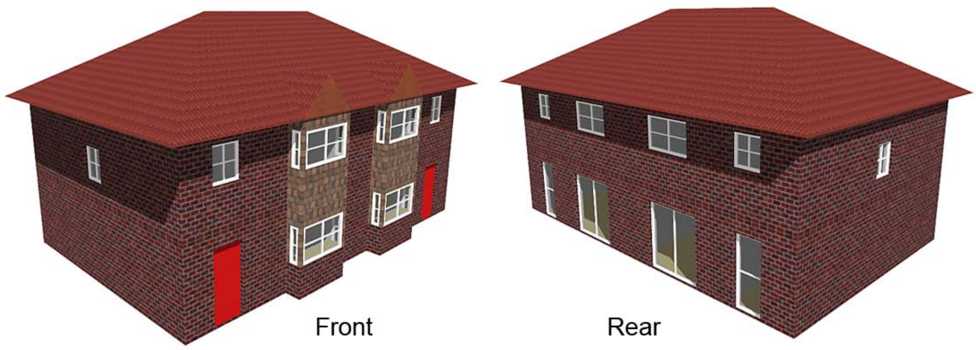

Figure 3.5 – Semi-detached house model

The house plans in Allen and Pinney (1990) were used to construct the semi-detached house model (Figure 3.5), which is typical of those built between the 1930s and 1950s. The internal floor area is 87m^2, just below the 95m^{2}average floor area from the EHCS data. The plans in Figure 3.6 show the living room and main bedroom are both at the front of the house. Figure 3.7 shows the glazing dimensions (note: the kitchen has no window and the door is assumed to be glazed). The external walls are constructed from bricks with an uninsulated cavity and the roof is covered with concrete tiles. The construction details are summarised in Table 3.2.

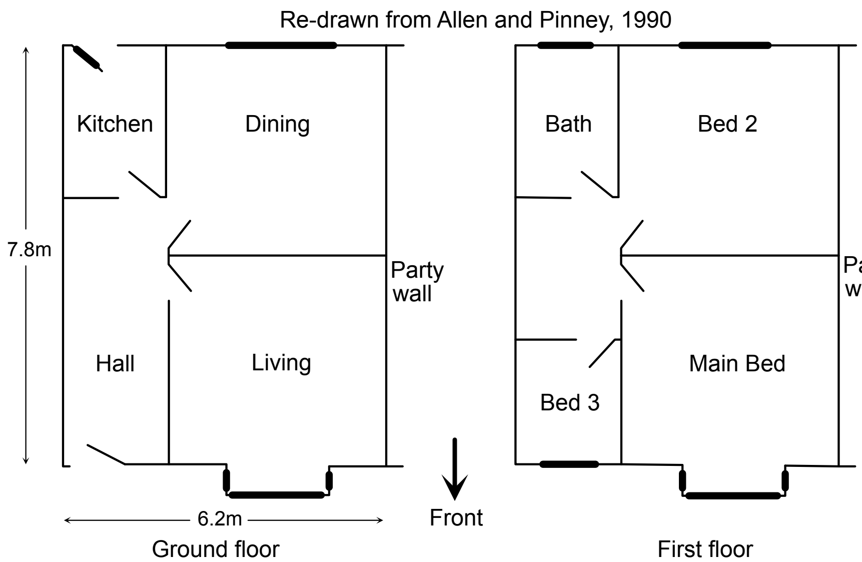

Figure 3.6 – Semi-detached house floor plans

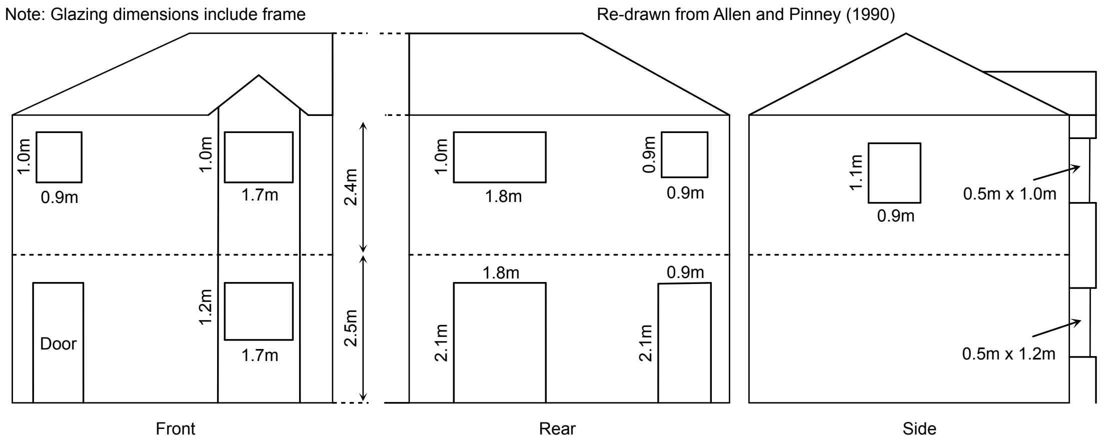

Figure 3.7 – Semi-detached house glazing

	Construction	U-value W/m^2 K	Solar absorptivity
External walls	Brick/brick with 0.05m uninsulated cavity and internal plaster 0.013m Total thickness 0.273m	1.43	0.7
Bay window walls (above living room windowsill and bedroom 1)	Tile-hung with air gap to plasterboard	2.38	0.7
Roof	Concrete tiles over roofing felt with 0.1m glass fibre joist level insulation	0.37	0.7
Ground floor	Cast concrete 0.1m over stone chippings to clay, uninsulated, carpet with underlay	1.10	0.6
First floor	Floorboards with carpet and underlay, air gap to plasterboard	1.30	0.6
Internal partitions	Single brick with plaster each side	1.87	0.5
Glazing	Pre-2002 double-glazing SHGC 0.708	2.70	-
Window frames	White uPVC	3.48	0.4
External doors	Wooden	2.25	0.5

Table 3.2 – Semi-detached house construction details

3.3.3 Flats

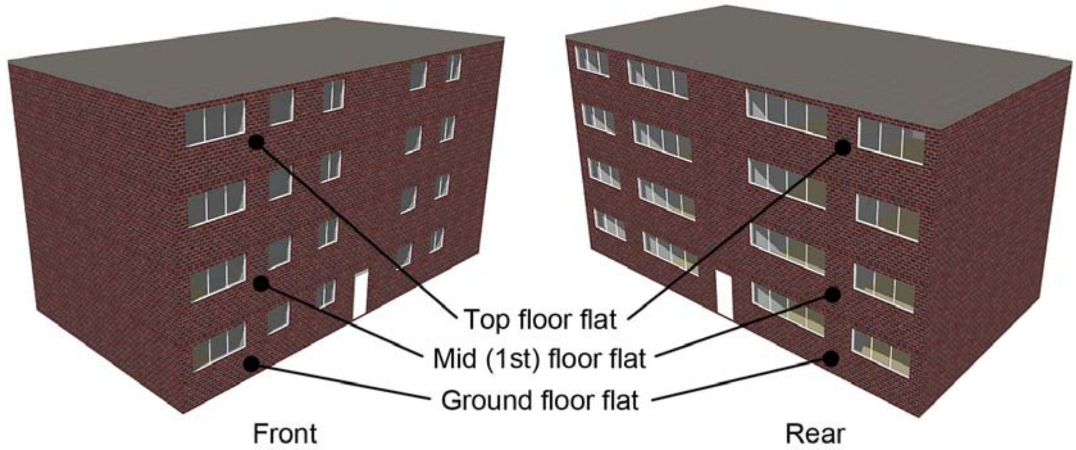

Figure 3.8 – Flats model

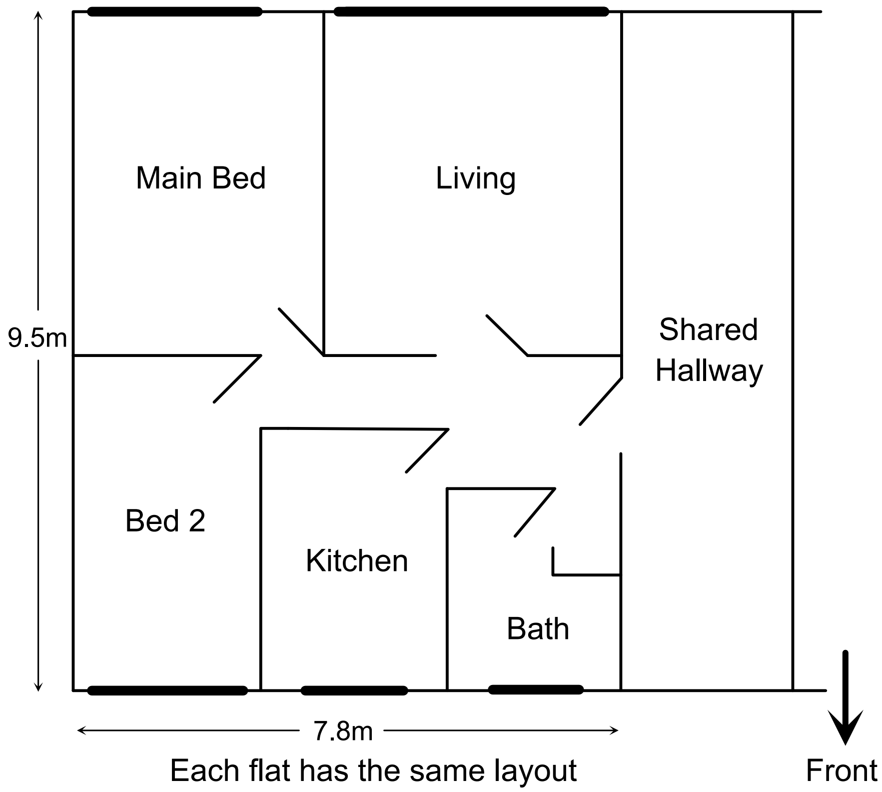

Figure 3.9 – Flats floor plans

Floor plans for the 1960s flats were obtained from estate agent details for flats in Greater London that met the EHCS criteria of 3-4 storeys and 59m^2 average floor area. Figure 3.8 shows the designBuilder model, constructed from the floor plans in Figure 3.9. The report *Your Home in a Changing Climate* (Arup, 2008) featured a 1960s block of flats and those construction details were used for this research (Three Regions Climate Change Group, 2008), with the exception of the single-glazed windows which were replaced with double-glazing consistent with the EHCS data.

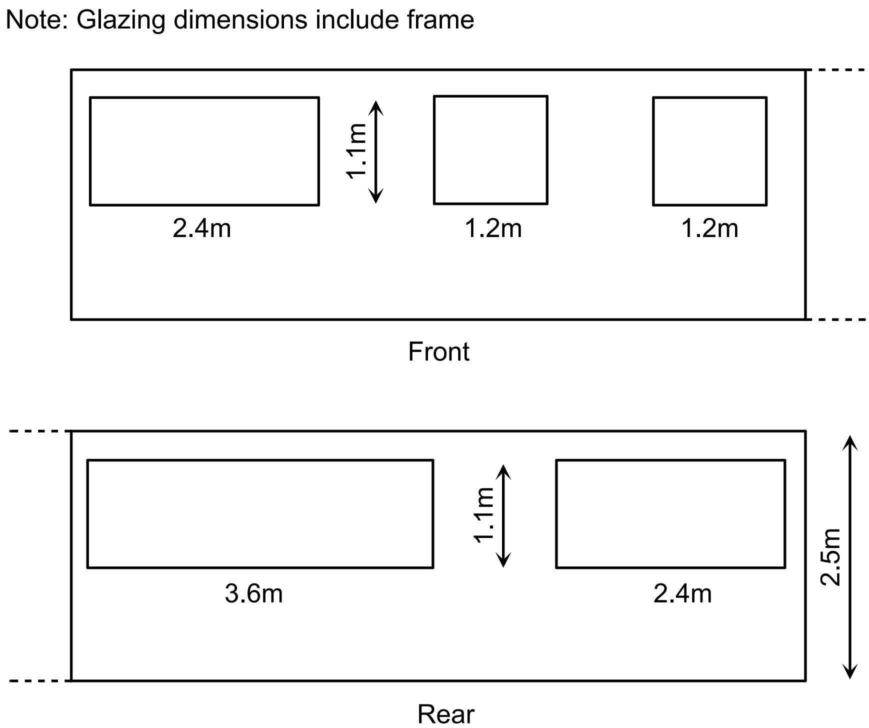

Figure 3.10 – Flats glazing

Each flat has the same layout, with the living room and main bedroom at the rear and the kitchen, bathroom and bedroom 2 at the front. The three flats chosen for simulation (ground, mid and top floor) are indicated in Figure 3.8. The floor area (per flat) for the simulation model is 67m^2, just above the EHCS average. The glazing dimensions are shown in Figure 3.10 and the construction details for the flats are summarised in Table 3.3.

	Construction	U-value W/m^2 K	Solar absorptivity
External walls	Brick/block with 0.05m uninsulated cavity and internal plaster 0.013m Total thickness 268mm	1.37	0.7
Roof	Cold roof construction: Asphalt, plywood, air gap, 0.05m mineral wool insulation, plasterboard	0.59	0.85
Ground floor	Cast concrete 0.1m over stone chippings to clay, uninsulated. Carpet with underlay	1.10	0.6
Intermediate floors	Cast concrete with underlay and carpet	1.64	0.6
Internal partitions	Plasterboard with air gap (within flats) Concrete block to hallways	1.89 1.54	0.5 0.5
Glazing	Pre-2002 double-glazing SHGC 0.708	2.70	-
Window frames	White uPVC	3.48	0.4
External doors	Front doors for flats lead to unconditioned communal hallways	2.25	0.5

Table 3.3 – Flats construction details

3.3.4 Detached house

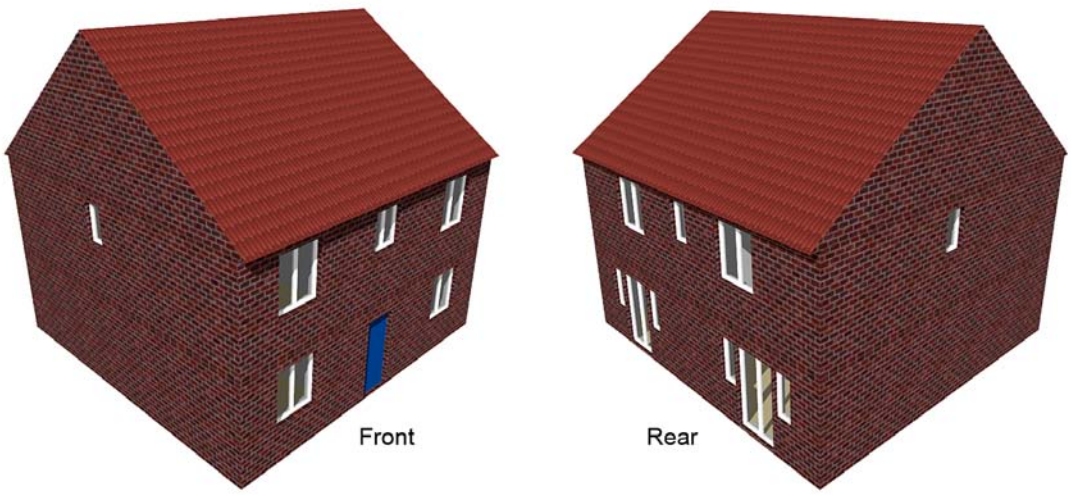

Figure 3.11 – Detached house model

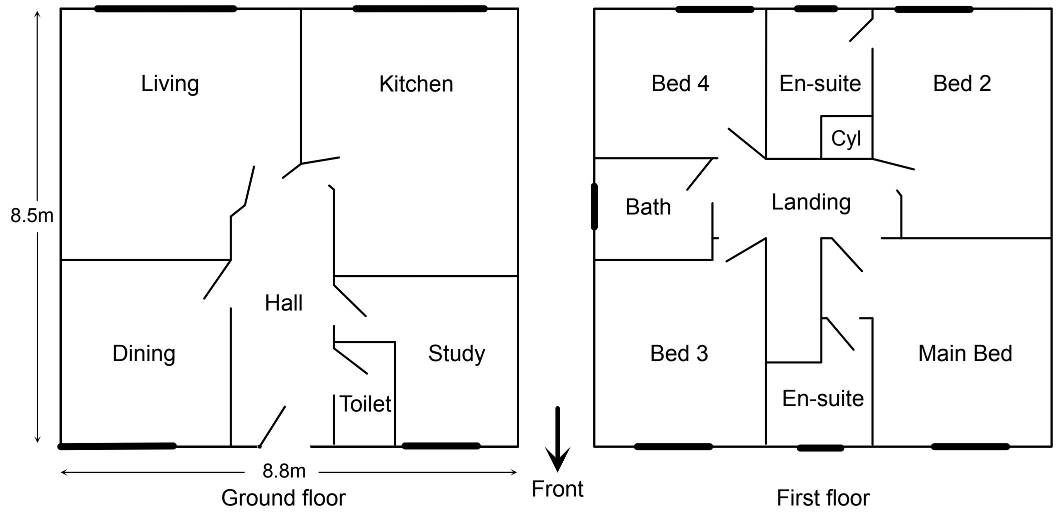

Figure 3.12 – Detached house floor plans

There are many modern detached house styles, which vary between builders. They can include rooms built into roof spaces with dormer windows or rooms over garages, to maximise the dwelling floor space within small building plots. A four-bedroom house design was selected (Figure 3.11) that is built by two of the larger house building companies in Southern England, Taylor Wimpey and Bryant Homes, to identical floor plans (Figure 3.12). The floor area is 127m^2, slightly below the EHCS average for detached houses in London and South East England. The glazing dimensions, including frames, are shown in Figure 3.13.

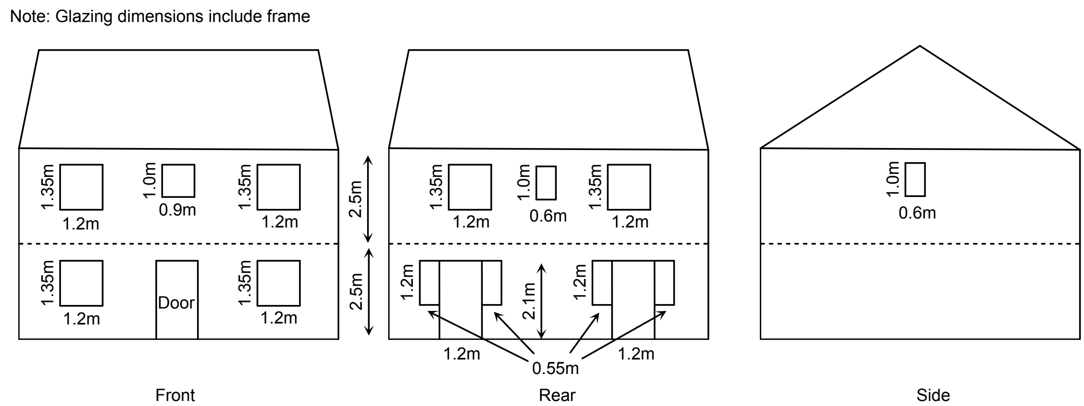

Figure 3.13 – Detached house glazing

The 2006 building regulations (Office of the Deputy Prime Minister, 2006b) specify a maximum area weighted average U-value for windows of 2.2 W/m^{2}K, which required a higher performance double-glazing than was specified for the other dwellings. The detached house double-glazing has a low emissivity (low e) coating to reflect heat back in to the room and increase the thermal performance. The construction materials and insulation details for the detached house are summarised in Table 3.4. The details were taken from an EPC and exceed the minimum required by the Building Regulations in force at the time.

	Construction	U-value W/m^2 K	Solar absorptivity
External walls	Brick/block with 0.1m extruded foam insulated cavity and plasterboard on dabs Total thickness 0.33m	0.27	0.7
Roof	Concrete tiles over roofing felt with 0.3m of joist level insulation	0.13	0.7
Ground floor	Block and beam with screed, insulated underneath with 0.075m PIR foam and air gap to clay soil	0.21	0.6
	Underlay and carpet (ceramic tiles to kitchen)	0.22	0.6
First floor	Chipboard with carpet and underlay, air gap to plasterboard	1.13	0.6
Internal partitions	Block with plasterboard on dabs	1.86	0.5
	Lightweight plasterboard with air gap	0.80	0.5
Glazing	Double-glazing: Part L2006 SHGC 0.691	1.96	-
Window frames	White uPVC	3.48	0.4
External doors	Wooden	2.25	0.5

Table 3.4 – Detached house construction details

3.4 Infiltration

The background infiltration settings for each dwelling type were determined using Table D.6 in Anderson et al. (2008). This table is reproduced in Table 3.5, with the assumptions used in each dwelling type. This method is also used in the Reduced Data Standard Assessment Procedure (RdSAP) worksheet for existing dwellings (Building Research Establishment, 2010). Any open fireplaces in the terraced and semi-detached houses are assumed to be sealed (possibly with fitted gas fires). The lack of open fireplaces and the presence of double-glazing reduces the background infiltration rate from that when constructed.

3.5 Occupancy profiles and internal gains

The simulation results presented in Chapters 6 to 8 concentrate on the living rooms and main bedrooms to quantify the overheating exposure of the residents. Other rooms are occupied at various times throughout the day and gains within these rooms are linked to occupancy. An assumption has also been made that windows will not be opened in unoccupied rooms, affecting gains and losses due to ventilation with outside air. In order to accurately model the total dwelling gains and losses the occupancy and gains profiles for each room must be set within the simulation models.

3.5.1 Occupancy

Two different occupancy profiles were used to compare the overheating exposure experienced by different types of residents. The first assumes occupancy by 2 working adults and school age children (number of children depending on house size), who are out of the dwellings during the daytime. The second occupancy profile represents the more vulnerable members of society and assumes two elderly residents (age 70

Building component	Infiltration contribution ACH	Terraced	Semi-detached	Flats	Detached
Building porosity					
solid walls	0.3	0.3	-	-	-
filled or partially filled cavity walls	0.3	-	-	-	0.3
unfilled cavity walls	0.35	-	0.35	0.35	-
timber frame walls	0.25	-	-	-	-
per storey above ground level	0.1	0.1	0.1	-	0.1
uncaulked suspended timber floor	0.2	0.2*	-	-	-
sealed suspended timber floor	0.1	-	-	-	-
unsealed loft hatch	0.025	-	-	-	-
Windows and doors					
if all openable	0.02	-	-	-	-
if all well fitting and draught sealed	0.05	0.05	0.05	0.05	0.05
if all loose and draught sealed	0.1	-	-	-	-
if all tight but not sealed	0.15	-	-	-	-
if all loose	0.25	-	-	-	-
if all very loose	0.35	-	-	-	-
no draught lobby on main door	0.05	0.05	0.05	-	0.05
Total air changes per hour (ACH)		0.7*	0.55	0.4	0.5

* Terraced house rear extension has a solid concrete floor reducing infiltration to 0.5 ACH for that area
Table reproduced from Anderson et al. (2008)

Table 3.5 – Model infiltration settings

plus), who occupy the dwellings all the time. The occupancy profiles were derived using data from the Time Use Survey, 2000 (Office for National Statistics, 2003).

The diary entries contain detailed information regarding activity and whether that activity was inside or outside the home, although without recording which room in the dwelling the activity took place. In most cases it can be assumed that when sleeping is recorded the person would be in their bed, although there are likely to be exceptions. For example elderly residents may have a short sleep during the day when they may be in a chair in the living room. Other activities are more difficult to pin down for location. When children recorded that they were using a computer or watching television it was assumed that they would be in their bedroom, although in some cases they may have been watching TV with their parents or using a family computer located in another room. Similarly, adults using a computer could be in the living room, spare bedroom or (in the case of the detached house) the study, depending on the location of the computer. Adult television viewing would mostly take place in the living room, but again there may be TVs in the kitchen, dining room or bedroom. Cooking activities would take place in the kitchen, but eating could happen in the kitchen, dining room or living room (TV dinners).

The survey data was therefore most useful for observing sleep patterns and hence bedroom occupied hours, although the resulting patterns also show general dwelling occupancy, with higher levels of daytime occupancy for elderly residents. For elderly residents the occupancy patterns are very similar for weekdays and weekends, whereas weekends are different to weekdays for families, where bedroom occupied periods are extended with morning lie-ins for some occupants. The diary entry dates also allowed sorting of the data to look at behaviour during the warmer months of the year (May to September).

The charts in Figure 3.14 show the weekday profiles for family (adults and children) and elderly residents when sleeping and when at home but not sleeping, for the months of May to September.

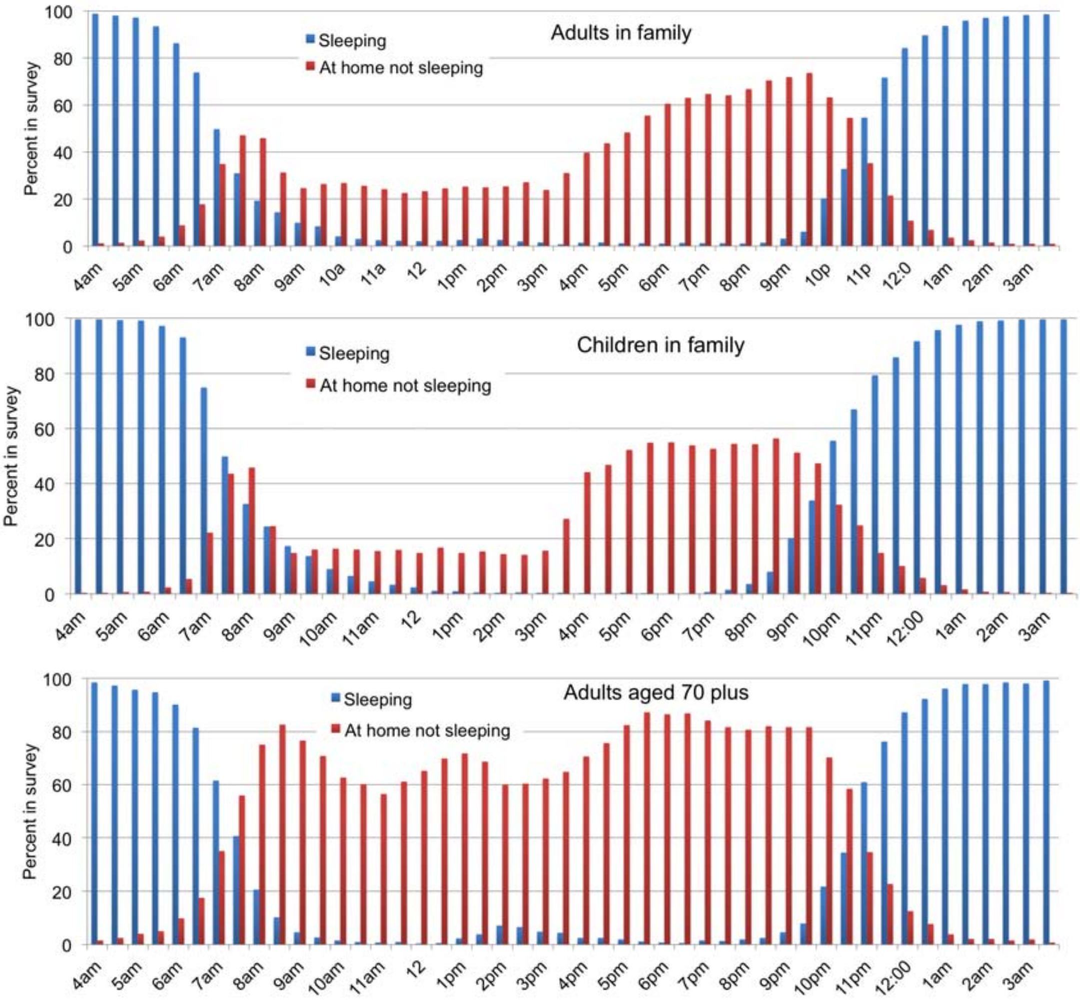

Figure 3.14 – Occupancy profiles (weekdays)

Some assumptions were made for the way the dwellings are used. The flats, terraced and semi-detached houses all have very small kitchens, which are not large enough to be used as dining areas. Therefore the dining rooms are used at meal times in the terraced and semi-detached houses, whilst a dining area in the living room is used for eating in the flats. The detached house has a large kitchen/diner which is assumed to be used for eating, leaving the dining room unused most of the time.

		Flats	Terraced	Semi-detached	Detached
Family profile	Adult bedroom	2230 - 0730	2230 - 0730	2230 - 0730	2230 - 0730
	Child bedroom	1600 - 0800	1600 - 0800	1600 - 0800	1600 - 0800
	Living room	0730 - 0830 1700 - 2300	1800 - 2300	1800 - 2300	1800 - 2300
	Kitchen	0700 - 0830 1600 - 1930	0700 - 0830 1600 - 1930	0700 - 0830 1600 - 1930	0700 - 0830 1600 - 1930
	Dining room	N/A	0730 - 0830 1700 - 1930	0730 - 0830 1700 - 1930	
	Bathroom	0700 - 0900 1900 - 2300	0700 - 0900 1900 - 2300	0700 - 0900 1900 - 2300	0700 - 0900 1900 - 2300
	Study	N/A	N/A	N/A	1800 - 2230
Elderly profile	Bedroom	2230 - 0800	2230 - 0800	2230 - 0800	2230 - 0800
	Living room	0730 - 2300	0900 - 2300	0900 - 2300	0900 - 2300
	Kitchen	0800 - 0900 1230 - 1330 1700 - 1800	0800 - 0900 1230 - 1330 1700 - 1800	0800 - 0900 1230 - 1330 1700 - 1800	0800 - 0900 1230 - 1330 1700 - 1800
	Dining room	N/A	0800 - 0900 1230 - 1330 1700 - 1800	0800 - 0900 1230 - 1330 1700 - 1800	Not used (kitchen/diner)
	Bathroom	0730 - 0830 2000 - 2300	0730 - 0830 2000 - 2300	0730 - 0830 2000 - 2300	0730 - 0830 2000 - 2300
	Study	N/A	N/A	N/A	Not used

Table 3.6 – Occupancy profiles

When doing annual overheating or energy use calculations it is important to account for different weekend occupancy patterns to produce accurate total figures, and this approach was adopted for the calculation of space heating energy use (Section 5.6). Elderly or infirm residents are more likely to be housebound and weekday/weekend profiles were seen to be very similar (Section 2.6.1). Family profiles showed that there was some increase in daytime occupancy at weekends, but the main change was seen to be longer sleeping duration due to lie-ins. However, it was assumed that a normal healthy family would not stay inside their dwelling on a heat wave weekend, and would be more likely to be outside, either taking advantage of the good weather or escaping the heat of the house. For the heat wave period the same profiles were used for each day of the week.

Ramped profiles are used to avoid sudden jumps in gains, so for example adults start to go to bed at 2230, when half occupancy is applied and by 2300 the full bedroom occupancy is applied. In the morning adults start to get up at 0700 and the bedroom is unoccupied after 0730. The ramped gains are accounted for in the occupancy gains in Table 3.7.

The review of occupancy profiles carried out in Section 2.6 and the data from the Time Use Survey (Office for National Statistics, 2003) was used to determine the family and elderly occupancy profiles for each room (Table 3.6).

3.5.2 Occupant heat gains

Internal gains for people were set using values from ASHRAE (2009), which is also the source of the values used in CIBSE (2006). The following metabolic rates were used in the simulations: 108 W/person for seated adults; 80 W/person for seated children; 72 W/person for sleeping adults and 54 W/person for sleeping children. Latent and sensible fractions are shown in Table 3.7, but during warm periods the latent heat gains have very little effect.

3.5.3 Equipment and lighting heat gains

This research presents overheating figures for living rooms and bedrooms, being the main occupied areas of the dwellings. Kitchens and bathrooms are exceptional cases due to the high gains from cooking and hot water use. However, the gains for these areas have been included in the simulation models as they will have some effect on temperatures in other rooms, even though the doors have been assumed to be closed for kitchens when cooking is taking place and at all times for bathrooms.

Gain source	Room	Gain (W)	Radiant fraction	Family Profile Operation	Elderly Profile Operation
Cooking	Kitchen (morning)	160	0.4	0730-0830	0800-0900
Cooking	Kitchen (evening)	1600	0.4	1700-1800	1700-1800
Fridge	Kitchen	50	0.2	24 hours	24 hours
TV	Living room	150	0.5	1800-2300	0900-2230
TV/Computer	Child bedroom	100	0.5	1600-2200	-
Hot water	Bathroom	77-98	0.2	24 hours	24 hours
Lighting	Living room	30	0.45	1930-2300	1930-2230
Lighting	Kitchen	54	0.45	As cooking	As cooking
Adults seated	Living room (x2)	108	0.3*	1800-2300	-
Adults cooking	Kitchen	189	0.3*	As cooking	As cooking
Adults sleeping	Bedroom (x2)	72	0.3*	2230-0730	2230-0800
Children seated	Living room/ bedroom	80	0.3*	1600-2200	-
Children sleeping	Bedroom	54	0.3*	2200-0800	-

* latent and sensible fractions for people are autocalculated in EnergyPlus according to metabolic rate and environmental conditions

Table 3.7 – Heat gains due to occupancy and equipment

The BRE standard dwellings for modelling document from 22 years ago (Allen and Pinney, 1990) sets evening cooker gains for heavy occupancy at 2380W and for light occupancy at 1700W, with reduced levels at breakfast and lunch times. However, cooker use has changed over the years with more dining out, supported by findings from research conducted for the European Commission (Bio Intelligence Service, 2010). This report states that more recent average UK cooker energy use per cycle is 1.6kWh and that cookers are used approximately 3 days per week. There will therefore be some days when there are no cooker gains to include, but it is not possible to determine which days within a heat wave period simulation should have no cooking gains. It was decided to include evening cooking gains of 1.6kW for one hour, with reduced gains of 160W for the breakfast period and no cooker use at lunch time. The kitchens are also assumed to contain a fridge, which is on all the time and rated at 50W.

Hot water gains for each dwelling were added to bathrooms at a constant 77W for elderly occupancy and 98W for family occupancy, based on the assumptions in Allen and Pinney (1990).

Appliance gains of 150W, typical of modern LCD televisions, were added to living rooms for occupied periods. For children's bedrooms 100W gains were added to allow for computers or games consoles, set to follow occupied hours in the evenings and switched off when asleep. No equipment gains were included for adult bedrooms. Low energy lighting was assumed and 30W lighting gains were included for living rooms in the evenings, with no lighting gains for bedrooms.

The occupant, lighting, equipment and hot water gains are summarised in Table 3.7.

3.6 Summary

This chapter has presented the assumptions used to construct the dwelling models for simulation, including construction details, occupancy profiles and internal gains.

The next two chapters will discuss the passive interventions applied to the dwellings and the modelling methodology used to produce the simulation results.

Chapter 4

Modelled interventions for passive cooling

4.1 Foreword

The previous chapter presented the dwelling types chosen for assessment in this research. The main aim of the research was to evaluate a range of passive interventions that could reduce overheating during heat wave periods, thereby eliminating or at least reducing the need for mechanical cooling. The research was further expanded to assess the effect of interventions on space heating energy use and to consider the cost of interventions to provide more complete retrofit guidance. This chapter provides details of the interventions selected for this research.

4.2 Introduction

This research only considers passive interventions, which by definition would not consume energy and therefore result in increased carbon emissions[1]. The range

[1]There may be some limited energy use required for low power fans to provide night ventilation if unattended windows cannot be left open.

	Terraced houses	Semi-detached houses	Flats	Detached house
Increase loft insulation	◆	◆		
Upgrade flat roof			◆	
External wall insulation	◆	◆	◆	
Internal wall insulation	◆	◆	◆	
Cavity wall insulation		◆	◆	
Internal window blinds	◆	◆	◆	◆
External window shutters	◆	◆	◆	◆
Curtains	◆	◆	◆	◆
External fixed shading	◆	◆	◆	◆
Solar reflective walls	◆	◆	◆	◆
Solar reflective roof	◆	◆	◆	◆
Low e triple-glazing	◆	◆	◆	◆
Night ventilation	◆	◆	◆	◆
Modified window opening	◆	◆	◆	◆

Table 4.1 – Modelled interventions by dwelling type

of interventions considered can be organised into three categories: solar control, insulation and ventilation. Not all of the interventions considered during the research are appropriate for every dwelling type. For example, installing additional external or internal wall insulation to a modern dwelling, which already has highly insulated cavity walls, may be difficult to justify. There may be other obstacles in the form of planning constraints, which could limit the range of potential interventions that change the external appearance. Cost may also be a limiting factor for the uptake of some interventions and is addressed later (Section 4.8).

Table 4.1 shows the range of modelled interventions, indicating to which dwelling type they were applied. Some are typical retrofit measures which could be considered for space heating energy use reduction, whilst others would only be applied for overheating reduction.

DesignBuilder (2011) was used to assign the physical interventions, either by constructing alternative building elements (wall insulation, glazing type, upgraded flat roof, external fixed shading) or adding shading devices from the built-in materials database (blinds, shutters and curtains). The behavioural interventions for ventilation control were modelled by adapting the control routines within the EnergyPlus EMS program (Section 5.4).

4.3 Cool coatings for walls and roofs

White or light coloured walls are very common in Southern European housing as a method for reducing solar heat gains (see Appendix F for an overview of vernacular dwelling design in warmer climates). Although light coloured surfaces can be found in the UK, especially for rendered buildings, the majority of dwellings are constructed using medium or darker coloured bricks and tiles. The wide range of solar absorptivity values found in the UK is evident from building construction materials databases. Tables in CIBSE (2006) show that absorptivity for light bricks falls in the range 0.36 - 0.62 and dark bricks 0.63 - 0.89, whilst roof tiles can have absorptivity values between 0.60 and 0.82.

Coating the surfaces with light coloured paint will reduce the solar absorptivity of walls and roofs. The IES-VE software Apache Tables (IES, 2011a) quotes an absorptivity value of between 0.3 and 0.5 for whitewashed roof or wall tiles. In recent years more advanced solar control coatings have been produced. Commercial companies, such as Watco (2012) claim a solar reflectance value of 88% (absorptivity 0.12) for their white solar reflective coating for use on walls or roofs.

Synnefa et al. (2007) used TRNSYS (DTM) to model the effect of cool coatings applied to roofs for a range of warm or hot locations. They did not include the UK, although Rome or Nice could be taken to represent possible future UK climates. The effect of changing the base case absorptivity from 0.8 to 0.15 was modelled, assuming a relatively high roof U-value (0.84 W/m^{2}K). Cooling load decreases of 47% and 59% were predicted for Rome and Nice respectively, with peak indoor temperature reductions of 3.0 °C and 2.6 °C. Further tests on a sample of locations showed a linear relationship between cooling load reduction and roof U-value.

Halewood and de Wilde (2008) used DTM (EnergyPlus) to simulate the effect of a cool paint (absorptivity 0.1) when applied to slate roof tiles on a terraced house (absorptivity 0.7). The roof space was insulated and using Rome weather data to represent a future UK climate they predicted a 6% increase in heating energy use and an 8% decrease in cooling load as a result of applying the coating.

Kolokotroni et al. (2011) conducted a case study on an office building constructed in 1995 with a flat roof (concrete slab with insulation , U-value 0.6 W/m^2K), calibrating TRNSYS simulation results with monitored temperatures. The base case roof had an asphalt surface with absorptivity 0.9 and the cool coating reduced this to 0.4. Average operative temperatures were seen to reduce by 2.5 °C, producing a good improvement in thermal comfort.

A BRE information paper on cool roofs (BRE, 2010) contains a table of reflectance and emittance values for a variety of cool roof coatings. The highest reflectance liquid-applied elastomeric white coatings are stated to have reflectance values between 0.75 and 0.85 (absorptivity 0.25 - 0.15). Emittance values remain unchanged from the uncoated surfaces, at between 0.85 and 0.95.

A cool surface coating was selected to match the highest performing coating in the BRE publication and the absorptivity settings for the modelled dwellings (Section 3.3) were changed to 0.15 for the light walls and light roof interventions, with emittance values left unchanged at 0.9. It should be noted that the absorptivity may increase over time as the surfaces become soiled or the coating degrades. Synnefa et al. (2006) identified an acrylic elastomeric coating as the most effective for daytime surface temperature reduction from a sample of 14 solar control coatings, but noted that performance degraded after exposure for 2 months.

4.4 External fixed shading

Figure 4.1 – External shading

The position of the sun in the sky at any given time of the day changes throughout the year. Intelligent shading design, such as that required for Passivhaus design (Hodgson, 2008), can reduce unwanted summer solar gains, whilst still allowing beneficial winter gains to reach the glazed surfaces.

To block all solar radiation throughout the day would require deep shading that extended well beyond each side of the window. However, there are practical considerations, such as wind loading and obstruction, that limit the acceptable size of shading devices. Shading options were assessed using solar shading visualisation in DesignBuilder (2011). Figure 4.2 shows images of the rear of the detached house model for south-facing and west-facing orientations on an August day.

The effect of blocking solar radiation was modelled by adding overhangs, to provide fixed shading above the south, east and west-facing windows. An overhang depth (horizontal projection from the wall) of 1.0m was found to block most of the direct solar radiation for south-facing windows during the summer period, whilst still being a practical size. Much larger overhangs would be required to totally block solar radiation on east and west-facing windows. Commercially available retractible shading devices (awnings) typically extend to about 2.0 m and these may be fitted to ground floor windows on east and west-facing facades. The 4pm image in Figure 4.2(b) shows that the awning provides solar shading down to the window sill level for the patio doors. The 1.0 m overhangs to first floor windows on the west-facing facade provide a small degree of solar shading later in the afternoon. The overhangs and awnings do not just shade the glazing, the sun path images in Figure 4.2 show how the wall areas around the windows are also shielded from direct solar radiation during the day.

(a) Rear south-facing, 1.0 m overhangs to all glazing

(b) Rear west-facing, 2.0 m overhangs ground floor, 1.0 m overhangs 1st floor

Figure 4.2 – Effect of fixed shading devices on detached house (rear)

The 2.0 m overhangs for east and west-facing ground floor windows were not considered for the flats or the terraced houses, where 1.0 m fixed overhangs were used. UK terraced houses are generally constructed at the edge of the pavement, close to the road. In the case of the flats, fitting and maintenance of retractible systems would be difficult (although there may be some scope for ground floor flats). Figure 4.3 shows the measurement details applied in the modelling.

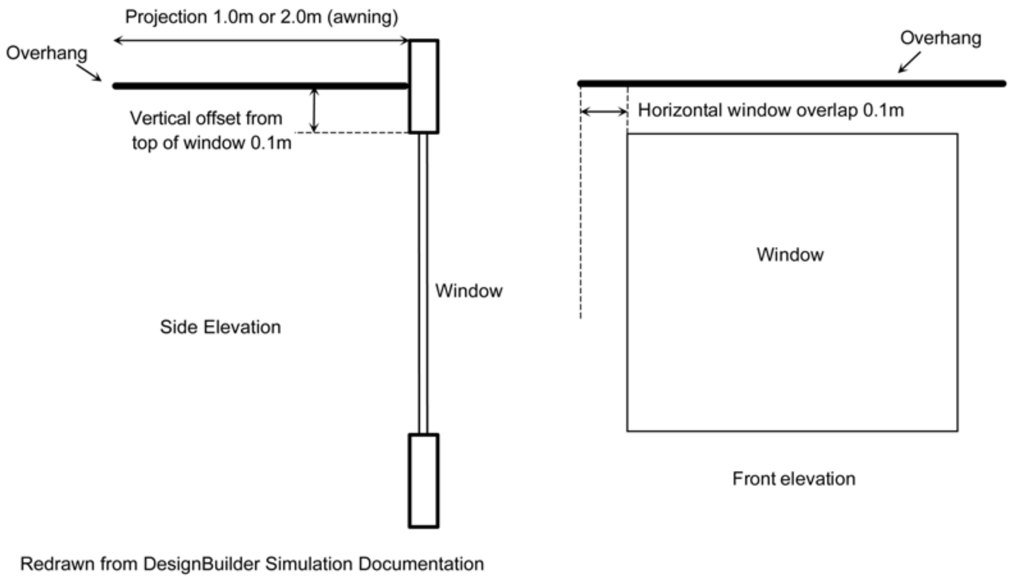

Figure 4.3 – Overhang modelling details for external shading

4.5 Glazing solar control

Shutters, blinds and curtains can be closed during the daytime to reduce solar heat gains through the glazing. External installation prevents the solar radiation reaching the window and is therefore more effective than internal installation, where much of the solar radiation has already entered the room before meeting the shading device. Table 4.2 shows the effect on solar heat gains of adding internal or external blinds for fast response (lightweight) or slow response (heavyweight) buildings (source: CIBSE (2006) Tables 2.3, 5.19 and 5.2).

Glazing and blind type	Solar heat gain (W/m^2)	
	Fast response building	Slow response building
Double glazing (clear/clear)	382	331
Double glazing with internal blind	294	294
Double glazing with external blind	176	192

South-west facing window, 14:30 21st June London. Total incident solar radiation on the surface 672 W/m^2 Source: CIBSE (2006) Tables 2.3, 5.19 and 5.2

Table 4.2 – Heat gains through glazing with internal and external blinds

4.5.0.1 Internal blinds

Figure 4.4 – Internal blinds

Internal blinds are available in a variety of styles (Figure 4.4) including roller, vertical and venetian, made from a range of fabrics, wood, metal and plastics. Dark fabric blinds will absorb a large amount of the solar radiation and transmit the energy as heat to the room, whereas reflective materials will absorb less of the solar energy. If the windows are open whilst the blinds are closed then some of the heat trapped between the blind and the glazing will be vented back to the outside.

The type chosen for this research was high reflectivity blinds from the slatted blinds section of the DesignBuilder materials database and the properties are summarised in Table 4.3. The blinds were controlled by a simple schedule, closing them between 0900 and 1800 during the heat wave period.

4.5.0.2 External shutters

Shutters can be of the more traditional hinged type (solid or louvred) or modern fitted roller shutters (Figure 4.5). However, one major limitation when considering shutters for use on UK dwellings would be the restriction on window opening, due to most UK windows opening outward. This restricts the ability to combine ventilation with shading in some cases. The same high reflectivity slatted blinds that were used for internal blinds (Table 4.3) were used as external shutters by changing their location to be outside the window panes. Using the same construction as the internal blinds also allowed direct comparison of internal and external positioning.

Figure 4.5 – External shutters

Blind with high reflectivity slats (used for both internal blinds and external shutters)	
Source	EnergyPlus
Blind-to-glass distance (m)	0.0150
Slat orientation	Horizontal
Slat width (m)	0.0250
Slat separation (m)	0.0188
Slat thickness (m)	0.0010
Slat angle (°)	45.0
Slat conductivity (W/m-K)	0.900
Slat beam solar and visible transmittance	0.000
Slat beam solar and visible reflectance (both sides)	0.800
Slat diffuse solar and visible transmittance	0.000
Slat diffuse solar and visible reflectance (both sides)	0.800
Slat emissivity (both sides)	0.900
Blind opening multipliers (top, bottom and sides)	0.500

Table 4.3 – Blinds and shutters properties(reproduced from DesignBuilder)

4.5.0.3 Curtains

Curtains are more generally made of fabric and depending on the material used will transmit some of the direct solar radiation. Darker fabrics will also absorb solar energy and transmit this the room as heat.

The effect of closing curtains during daytime hours was modelled by adding close weave medium drapes from the diffusing blinds section of the materials database in DesignBuilder. The operation of the curtains was controlled by a simple schedule, which closed the curtains during daytime hours (0900 - 1800). The curtain properties are summarised in Table 4.4.

Drapes - close weave medium	
Source	BLAST
Thickness (m)	0.003
Conductivity (W/m-K)	0.100
Solar transmittance	0.050
Solar reflectance	0.300
Visible transmittance	0.050
Visible reflectance	0.300
Long-wave emissivity	0.900
Long-wave transmittance	0.000
Shade-to-glass distance (m)	0.050
Shade top and bottom opening multiplier	1.000
Shade left and right-side opening multiplier	0.000
Shade airflow permeability	0.000

Table 4.4 – Curtain properties (reproduced from DesignBuilder)

4.5.0.4 Low e triple glazing

An alternative method for reducing solar energy transmission through windows is to fit glazing with a low solar heat gain coefficient (SHGC). The SHGC is the fraction of the incident solar radiation that enters the room and combines the directly transmitted solar radiation and heat from solar radiation absorbed by the glazing itself that is subsequently transferred to the room. Replacing the glazing would be a very expensive option and could only realistically be considered if the windows were in need of replacement. Low emissivity (low e) metallic coatings can reduce heat losses and improve the thermal efficiency of the windows if the coating is on the inner surfaces of the glazing, such that it reflects heat back into the room. This is the case with the default 2006 regulations double-glazing specified in the detached house model. If coatings are applied to outer surfaces, solar radiation is reflected

Layers	3 x 0.003m with 2 x0.006m air gaps Outer and inner panes low e coated
Total solar transmission (SHGC)	0.472
Direct solar transmission	0.358
Light transmission	0.661
Glazing U-value (W/m^2K)	1.57
uPVC frame U-value (W/m^2K)	3.48

Table 4.5 – Low e triple-glazing

before it can enter the room, thus reducing solar heat gains. Installing triple-glazing would also increase the thermal efficiency of the windows through lower U-values compared to the base case double-glazing.

Research by Barry and Elmahdy (2007) compared the performance of low and high SHGC versions of low e double-glazing in two test houses in Canada. Their results showed a 7.8% increase in heating energy use with the low SHGC glazing compared to the high SHGC version. However, in summer the low SHGC version reduced cooling energy use by 27%.

The low e triple-glazing used in the simulations (Table 4.5) was sourced from the EnergyPlus glazing database, the detailed properties of the glazing materials are contained in Table A.2 in Appendix A. The EnergyPlus data is spectrally averaged and does not include information regarding the effect of the low e coating on different wavelengths.

Films are also available that can be applied to existing glazing and reduce solar heat gains even further, although at the penalty of much reduced visible light transmittance. These may cause issues with lower light levels, particularly in winter, and were not considered in this research.

4.6 Insulation

Figure 4.6 – Insulation: External, Internal and Loft

Insulation upgrades are usually considered for reducing heating energy use, but their effect on dwelling overheating should also be considered. Insulation can reduce the transfer of heat gains into a dwelling from the outside, thereby helping to reduce overheating. However, they can also more effectively retain heat gains within the dwellings, which may lead to increased overheating.

4.6.1 Wall insulation

The four simulation models contain three different external wall construction types: insulated cavity walls for the detached house, uninsulated cavity walls for the flats and semi-detached houses and solid brick walls for the terraced houses. Figure 4.7 shows the three types of wall insulation (internal, external and cavity) suitable for cavity wall dwellings, which are limited to internal and external insulation for the terraced house solid walls. The high levels of insulation already present in the modern detached house would suggest that adding extra insulation, although possible, would be difficult to justify and was therefore not considered.

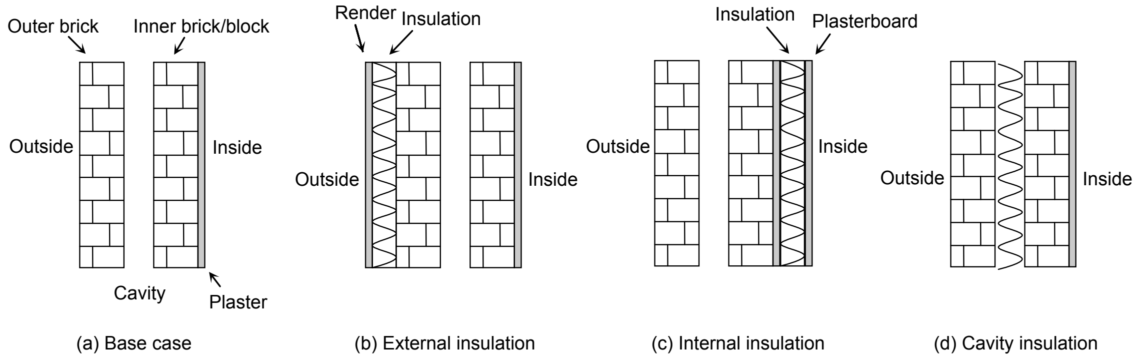

Figure 4.7 – Wall insulation

Current UK Building Regulations (HM Government, 2010a) specify a maximum wall U-value of 0.3 W/m^2 K for upgrades to existing walls using external or internal insulation and 0.55 W/m^2 K for insulated cavity walls. However, this research commenced before the publication of the current regulations (published in December 2010). The previous regulations (Office of the Deputy Prime Minister, 2006c), which were used to set target thermal standards in this research, required a maximum wall U-value of 0.35 W/m^2 K for external or internal insulation.

External wall insulation traditionally involves the addition of a layer of insulating material to the outer face of external walls, with a further protective render coat. Other novel products have appeared on the market in recent years, including insulated render (INCA, 2011). This combines the insulation (in beads) with the render and it is built up in layers, though the maximum thickness is limited. Internal wall insulation usually involves dry lining the external walls with a layer of insulating material, placed between wooden battens, to which an internal plasterboard layer is fitted. Many dwellings built between the 1930s and 1970s have cavity walls, a large proportion of which are still uninsulated. Cavity wall insulation involves injecting insulating material (usually blown mineral fibre) in to the cavity. The cavity width in older dwellings is typically 50 to 65mm, restricting the maximum achievable U-value to around 0.5 W/m^2 K, depending on the original wall construction.

		Terraced	Semi-detached	Flats
External	Render thickness (m)	0.025	0.025	0.025
	Insulation thickness (m)	0.060	0.052	0.052
	U-value (W/m^2K)	0.35	0.35	0.35
Internal	Plasterboard thickness (m)	0.013	0.013	0.013
	Insulation thickness (m)	0.060	0.052	0.052
	U-value (W/m^2K)	0.35	0.35	0.35
Cavity	Insulation thickness (m)	-	0.050	0.050
	U-value (W/m^2 K)	-	0.57	0.57

Table 4.6 – Wall insulation details

Phenolic foam insulating boards were used for the external and internal insulation layers, whilst mineral fibre was used for cavity insulation. The thickness of the insulation layers for internal and external wall insulation were adjusted to produce the required U-value of 0.35 W/m^2 K, which could be checked on the 'Calculated' tab when editing the modified wall constructions in DesignBuilder. The resulting construction layers and final wall U-values are given in Table 4.6 (the detailed material properties are given in Appendix A). The practical issues, benefits and disadvantages of each type of wall insulation are discussed in Section 9.5.

The base case version of the terraced houses have a background infiltration level higher than the other dwelling types at 0.7 ACH. It has been assumed that some improvement to draught proofing would occur during the installation of wall insulation and the background infiltration for the versions with external and internal wall insulation have been reduced to 0.5 ACH.

4.6.2 Loft insulation

Although some older properties with pitched roofs have little or no loft insulation, the vast majority now have some joist level insulation. Typical thicknesses were found to be approximately 100mm for the older properties in the EHCS survey (Section 3.2). Increasing the level of loft insulation to 250mm, by cross-laying 150mm rolls of fibre glass over the existing insulation, is a common energy saving upgrade supported by grants from local authorities and energy companies. Increasing insulation above the top floor ceilings may also reduce the transfer of heat from the loft space to the rooms as the loft temperature rises during periods of high solar gain (assuming dark, solar absorbing roof tiles). Conversely, higher levels of loft insulation may restrict the ability to discharge heat from the bedrooms to the roof space overnight.

With the exception of the modern detached house, the level of loft or roof insulation for each base case dwelling type (Section 3.3) produced roof U-values above the Building Regulation level of 0.25 $W/m^2 K$ (Office of the Deputy Prime Minister, 2006c). For the terraced and semi-detached houses the loft insulation intervention increased joist level insulation thickness to 250mm, producing a modified roof U-value of 0.15 $W/m^2 K$, exceeding the Building Regulations value. For the flats, the increase in roof insulation was achieved by replacing the existing poorly insulated roof with one conforming to the 2006 Part L Building Regulations (Office of the Deputy Prime Minister, 2006c). The DesignBuilder constructions database contains a lightweight Part L 2006 flat roof that was used for the replacement roof. It has a waterproof felt outer surface over a plywood deck and 140mm EPS foam insulation with a plasterboard ceiling as the innermost layer, producing a U-value of 0.25 $W/m^2 K$. The detached house loft insulation already exceeds the Buildings Regulation value and was therefore not considered for upgrade.

4.7 Ventilation

The two ventilation interventions are both behavioural changes, which were simulated by modifying control strategies using the Energy Management System (EMS) in EnergyPlus. The methodology is discussed in Section 5.4 and example modified EMS routines are found in Appendix C.

4.7.1 Night ventilation

Occupants will generally open bedroom windows at night during very hot weather to achieve thermal comfort, although other windows (particularly ground floor ones) are likely to stay closed due to security concerns (Liddament, 2001). If the windows in unoccupied rooms can be opened at night, the cooler air can be used to flush the warm air from the dwelling and, if there is sufficient thermal mass, pre-cool the building fabric in advance of the next day. Indeed night ventilation becomes very important for higher thermal mass buildings. If the heat stored in the mass cannot be removed at night the overheating problem will compound on subsequent days. An example of night ventilation provision incorporated into a window design is shown in Figure 4.8.

Figure 4.8 – Night ventilation grill (BRE Innovation Park)

Artmann et al. (2007) investigated the potential for night ventilation of dwellings for 259 weather locations around Europe. Night ventilation is suitable for locations that experience large diurnal swings in outdoor temperature and their results showed a high potential for night cooling in Northern European locations (including the UK) and a significant potential for Central European locations. Givoni (1994) recommends that the minimum night temperature should drop below around 20 °C for night ventilation cooling to be effective. During the 2003 heat wave the London night temperature was below 20 °C on all but two of the nights, on one it dropped to 21.7 °C and the other 20.2 °C. Climate change is predicted to reduce the effectiveness of night ventilation in the UK, with London experiencing more frequent summer periods where night ventilation alone will not be sufficient to achieve thermal comfort (Artmann et al., 2008).

Santamouris et al. (2010) assessed the efficiency of night ventilation for Greek dwellings, where air conditioning is common in more affluent houses. The Greek climate may be seen as representative of a future Southern UK climate under higher emissions scenarios and night ventilation was seen to decrease cooling energy use by an average 26%. The study cases covered a range of air change rates from 2 to 30 air changes per hour (ACH) and an almost linear relationship was found between the energy contribution of night ventilation and the air change rate. Orme and Palmer (2003) estimate that air change rates of the order of 10 ACH may be needed for night cooling to be effective in UK dwellings. They also warn that in certain circumstances over cooling of the thermal mass may occur if the night ventilation is not controllable leading to possible heating energy use in early morning periods, though this is not likely to be the case during heat wave periods.

The base case models assume that windows are closed when rooms are unoccupied (Section 5.3). The night ventilation intervention allows ventilation of unoccupied rooms, which is simulated by increasing the room air change rate during the night for those rooms. The ventilation is activated if the room air temperature is above 22 °C and is set to the Building Research Establishment (2010) values depending on dwelling type (Section 5.3). Although this is being considered as a passive intervention, there may be issues with noise or security in urban or city locations, which could limit window opening. To achieve the required ventilation rate vents with low power fans may have to be fitted.

4.7.2 Window opening behaviour

Several studies have been carried out monitoring window opening behaviour in office buildings (e.g. Raja et al., 2001; Rijal et al., 2007; Inkarojrit and Paliaga, 2004; Brager et al., 2004; Haldi and Robinson, 2008; Nicol et al., 2007), but comparatively little is known about the operation of windows in dwellings. Andersen et al. (2009) used questionnaire based research to record window opening as a function of outdoor temperature in Danish dwellings, but the survey only recorded whether the window was open or closed and not the extent of opening. The type of building can have a large impact on the indoor temperature at any given outdoor temperature, therefore window opening in modelling studies is more usually based on the indoor temperature.

The threshold indoor temperature above which window opening commences varies between the studies. Nicol et al. (2007) showed that for office occupants the probability of windows being open at an indoor globe temperature of 20 °C is approximately 0.1, rising to 0.9 at 28 °C. Raja et al. (2001) also found that 20 °C was the temperature above which window opening started to rise steeply, with almost 100% open by 27 °C. Two studies by Rijal et al. (2008) in naturally ventilated UK office buildings showed that window opening started at 20 °C in one and 22 °C in the other, with windows fully open by 26 °C and 28 °C respectively.

Modelling studies in dwellings have used a variety of window opening assumptions. Holmes and Hacker (2007) simulated window opening by increasing the ventilation air change rate when the internal temperature rose above 24 °C, reaching maximum opening by 28 °C. The assumptions used in this research for all cases (except where the window rules intervention was applied) followed the CIBSE (2005) window opening rules, in which opening commenced at an internal temperature of 22 °C, with windows opening linearly and being fully open by 28 °C.

4.7.2.1 Window opening rules

If windows are opened during hot weather there may be certain times of the day (peak afternoon hours) where the outdoor air temperature exceeds the indoor air temperature. If windows are opened during these periods the indoor air temperature will rise. A possible intervention is therefore to prevent windows from opening if this situation occurs and this was one of the adaptation strategies applied in CIBSE (2005).

The window rules intervention prevents windows from opening if the outside air temperature is greater than the room air temperature, which is simulated by reducing the room air change rate for natural ventilation to zero, leaving the background infiltration rate for fresh air ventilation. It may be difficult for occupants to know when to open or close their windows based on the temperature difference, which means that this intervention may require some sort of warning system. The ventilation control methodology is covered in detail in Section 5.3.

4.8 Intervention costs

Meetings with stakeholders in the early stages of the research revealed that cost was a major concern and a possible barrier to the uptake of interventions. Including cost information is therefore valuable and allows selection of the most cost effective retrofit package.

Some of the available overheating reduction advice publications include approximate costs for interventions. However, the range of figures varies widely and is complicated by subsidies that may be available to households (for example loft or cavity wall insulation), but which may not be available to commercial landlords. Economies of scale will also mean that some interventions will be cheaper for landlords with a large stock portfolio, buying in bulk. Adapting groups of houses in one go, such as blocks of flats or rows of terraced houses, will reduce costs further.

The policy maker report Your Home in a Changing Climate (Arup, 2008) adopts a price banding approach, grouping adaptation measures into low (up to £100); medium (£101 - £1,000) and high (£1001+). However, it is difficult to extract accurate price information from this report. For example, the report states that installing reflective blinds can be low, medium or high cost. However a table of more detailed costs, for a limited range of measures, is provided for a case study 3-bedroom 1930s semi-detached house.

No single source of cost information could be found that covers the full range of modelled interventions. The EST (2012) provide some cost information on their website for insulation products, with subsidised and unsubsidised estimated costs. The UK government Department of Energy and Climate Change (DECC, 2010a) published assumed costs for insulation upgrades as part of its assessment of impacts for household energy efficiency upgrades. Costs are provided for both local authority properties and individual householders, based on a 3-bed semi-detached house. The Energy Saving Trust and the Energy Efficiency Partnership for Homes commissioned a report in 2009 (EST, 2009) that reviewed the full installed costs for solid wall insulation across a range of suppliers and sources. Costs are provided for multiple installations as well as single dwellings.

The Building Cost Information Service (BCIS), a division of the Royal Institution of Chartered Surveyors (RICS), publish two price guides that cover domestic refurbishment: The Greener Homes Price Guide (BCIS, 2008a) and The Property Makeover Price Guide (BCIS, 2008b). These two publications provide a resource for householders, with guideline costs for a range of home improvement measures. However, some of the prices quoted in the BCIS publications are very high compared to other sources. For example, external wall insulation is stated to cost £28,519 (exc. VAT) for a semi-detached house, compared to around £13,000 from the EST (2009). For property professionals, Spon's Architects' and Builders' Price Book (Langdon, 2011) provides a resource for costing building works. Prices can be calculated based on unit costs and scaled for each building and some of the intervention costs could be estimated using this resource.

Further prices for comparison were obtained from online searches of manufacturer and supplier websites. Table 4.7 summarises the costs for a range of interventions obtained from the sources outlined above.

Table 4.7 demonstrates the wide variety of costs that can be found for the interventions. Different users of this research output will have independent views on realistic costs, depending on whether they are local authorities, landlords or private householders. The cost information is intended as a guide and it is suggested that when a combination of interventions has been located that delivers the desired performance for overheating reduction and space heating energy use at an approximate price point, the user substitutes their own figures to arrive at a cost for the retrofit package. It was decided to use costs based on single household retrofit (i.e. no bulk discounts were included) and the costs are exclusive of tax (VAT). Subsidised prices have also been used for cavity and loft insulation, where grants are available. The EST (2009) figures were used for external and internal wall insulation, because they were based on a wide survey of realistic installed costs (although from 2009). Langdon (2011) was used to provide costs for solar reflective coatings for the walls and roof (the guide contains a breakdown of material and installation costs); the cost of fixed external shading, based on per metre installed costs for brise soleil shading devices and the cost of upgrading the flat roof on the block of flats (assuming the cost is shared equally between all 8 flats in the block).

Low e triple-glazing is not very common in the UK and obtaining quotes was difficult. (BCIS, 2008b) contains prices for double-glazing replacement and these were

Intervention	Cost for a 3-bed semi-detached house (£ exc. VAT)							
	A	B	C	D	E	F	G	H
Add loft insulation	-	100* - 300	-	150*	425	282	128 (DIY)	-
Cavity wall insulation	1,100	100* - 300	-	150*	340	1,620	-	-
External wall insulation	-	Up to 10,830	12,560	-	28,519	4,800	7,600	-
Internal wall insulation	-	Up to 7,080	6,960	-	5,440	-	5,000	-
Low e triple-glazing	5,000	-	-	11,000	6,300**	-	-	-
Solar coating walls	3,750	-	-	-	2,894	-	-	1,164
Solar coating roof	-	-	-	-	-	-	-	1,060
External fixed shading	1,700	-	-	-	-	-	-	Up to 4,126
External shutters	-	-	-	4,510	-	-	-	-
Internal blinds	-	-	-	2,200	-	-	-	-

A: Your Home in a Changing Climate (Arup, 2008)
B: Energy Saving Trust website (EST, 2012)
C: Solid wall insulation supply chain review (EST, 2009)
D: Commercial installed quotes
E: BCIS Greener Homes Price Guide / Property Makeover Price Guide (BCIS, 2008b,a)
F: DECC local authority price (DECC, 2010a)
G: DECC private householder price (DECC, 2010a)
H: Spons' Architects and Builders' Price Book (Langdon, 2011)
*: Denotes subsidised price **Based on commercial information add 50% premium for low e triple-glazing

Table 4.7 – Intervention costs from various sources

	Cost per unit (£ exc. VAT)	Cost for End Terraced	Cost for Mid Terraced	Cost for Semi-detached	Cost per Flat	Cost for Detached	Sources (see Table 4.7)
Loft insulation (top-up)	-	150	150	150	-	-	B,D,G
Upgrade flat roof	$102/m^2$	-	-	-	2,183	-	H
External wall insulation	$157/m^2$	13,973	8,478	12,560	8,635	-	C
Internal wall insulation	$87/m^2$	7,743	4,698	6,960	4,785	-	C
Cavity wall insulation	-	-	-	200	200	-	B,D
Internal blinds	Varies	1,600	1,600	2,200	1,200	2,600	D
External shutters	Varies	3,272	3,272	4,510	3,150	5,694	D
Fixed shading***	315/m	1,260 - 2,205	1,260 - 2,205	2,394 - 4,126	1,701 - 3,717	2,363 - 5,575	H
Low e triple-glazing	Varies	5,100	5,100	9,460	6,100	13,000	E,D
Night ventilation	-	400	400	400	200/zero**	400	D
Solar coating walls	$14.55/m^2$	1,295	786	1,164	800	2,343	H
Solar coating roof	$20/m^2$	860	860	1,060	428	1,600	H

* bay windows and patio doors = 2 windows **1st and top floor flats assume windows can be left open at night without security issues ***Cost varies according to orientation

Table 4.8 – Intervention costs

increased by 50%, in line with guidelines on commercial websites, to provide an estimated cost for low e triple-glazing. The costs of internal blinds and external shutters were also difficult to estimate and for these interventions commercial quotes were used. Night ventilation may be a zero cost intervention in some cases, for example flats above the ground floor, where windows may be left open at night in unoccupied rooms. In other cases it is likely that either security measures (window grilles or restrictors) or ventilation fans may have to be fitted. The cost of these will vary considerably and an allowance has been made for such measures for each dwelling. Table 4.8 contains the cost assumptions used for each dwelling type.

4.9 Combined interventions

The interventions in Table 4.1 were also applied in combination for each dwelling type. If all possible combinations of interventions were to be modelled for the four dwelling types it would require 164,864 separate simulations for each complete batch (one weather file). To reduce the number of simulations to a more manageable size a decision was taken to eliminate certain intervention combinations. Although it would be possible, it is unlikely that different types of wall insulation would be fitted to a wall at the same time and therefore combinations of wall insulation were eliminated. The same argument was used for glazing solar control by closing curtains, internal blinds or external shutters. The modern detached house already has good levels of wall and loft insulation, therefore the insulation upgrade interventions were not applied in the detached house model.

The addition of combined interventions to the simulation models was managed through a parametric control interface (jEPlus), which is discussed in Section 5.2.3.

4.10 Summary

This chapter has discussed the range of passive interventions that were applied to each dwelling, providing background information to support the choice of material properties and construction details. The potential impact on heating energy use was discussed and costs of interventions estimated from a variety of sources. The interventions are summarised in Table 4.9.

Category	**Intervention**	**Changed properties**	
		U-value (W/m^{2}K)	Absorptivity
Insulation	Increase loft insulation to 0.25m (terraced/semi-detached)	0.16	-
	Upgrade flat roof (flats)	0.16	-
	External wall insulation (terraced, semi-detached, flats)	0.35	-
	Internal wall insulation (terraced, semi-detached, flats)	0.35	-
	Cavity wall insulation (semi-detached, flats)	0.57	-
Solar Control	Internal blinds, closed 0900-1800	-	-
	External shutters, closed 0900-1800	-	-
	Curtains, closed 0900-1800	-	-
	External fixed shading above south, east and west windows	-	-
	Light walls - solar reflective coating	-	0.15
	Light roof - solar reflective coating	-	0.15
	Low e triple-glazing (SHGC 0.472)	1.6	-
Ventilation	Night ventilation of unoccupied rooms	-	-
	Window rules - prevent windows opening in occupied rooms if outside air temperature is higher than inside air temperature	-	-

Table 4.9 – Interventions summary (details in Sections 4.3-4.7)

Chapter 5

Dynamic thermal modelling

5.1 Foreword

The previous two chapters discussed the dwelling types and interventions chosen for simulation. This chapter discusses the choice of simulation software and describes how it was adapted to enable the large scale parametric simulations required for this research.

5.2 Modelling tools

The aim of the research was to assess the effectiveness of selected interventions for reducing overheating during heat wave periods, whilst also predicting their effect on annual space heating energy use. Of particular interest for this research are the zone (or room) operative temperatures (Section 2.3.3), to enable calculation of the degree of overheating on an hourly basis. Annual sensible heating energy use was also required to predict the effect of interventions on space heating energy use.

The research project investigated the effect of single and combined interventions for a range of dwelling types, each for two occupancy profiles and four orientations.

This required a large number (tens of thousands) of parametric simulations, which limited the choice of software tools to those that could be run in batch mode, allowing parameters to be changed automatically between simulations. The IESD has a 256 core cluster computer and it was therefore desirable to use a simulation tool that could take advantage of this parallel processing power to reduce simulation run times.

Integrated Environmental Solutions Virtual Environment (IES) software package (IES, 2011b) was initially considered because of familiarity through previous use, its user-friendly interface and the fact that it is validated and widely used in both academia and industry. However, due to the closed (black box) nature of IES, it would have been difficult and time consuming to do the large number of parametric simulations required for this research. There was also no existing mechanism to utilise the parallel processing power of the IESD cluster with IES.

5.2.1 EnergyPlus

In 2001 The U.S. Department of Energy released a new building energy simulation tool, EnergyPlus (Crawley et al., 2001). It was designed to replace two existing simulation tools, BLAST and DOE-2 and, although based on the best features of these two programs, was written with all new code. EnergyPlus has a simulation manager that controls the whole process and adopts a modular approach, coupling the various components and allowing easy addition of new modules (Figure 5.1). EnergyPlus has undergone regular revisions over the years, the current release is version 7.0, which was released towards the end of 2011. This research used version 6.0 (U.S. Department of Energy, 2010), released in October 2010.

Heat and mass balance simulation is coupled with the buildings systems simulation, calling on other modules as required to calculate the various gains and ventilation exchanges. The input data for EnergyPlus simulations is contained in a text file

Image removed from electronic version of the thesis to comply with copyright - see reference

Figure 5.1 – EnergyPlus - reproduced from U.S. Department of Energy (2011c)

called the Input Data File (IDF). In addition, the IDF can be changed to an IMF (Input Macro File) allowing substitution of whole sections of input data, such as wall constructions or ventilation control strategies. This enables the user to change sections of the input file and control these changes using a third party interface (Section 5.2.3). EnergyPlus is also platform independent and can be downloaded in PC, Mac or Linux versions.

EnergyPlus allows user selection of calculation methods, including the heat balance and surface convection algorithms. The default heat balance algorithm uses Conduction Transfer Functions (CTF). Other algorithms are included for research use, including Conduction Finite Difference (required for modelling phase change materials), but the default CTF algorithm was used for this research. Recent versions of EnergyPlus have allowed the user to select adaptive algorithms for inside and outside surface convection, which are selected by default in DesignBuilder. This allows EnergyPlus to dynamically select the appropriate convection algorithm based on conditions for each surface, which was the method selected for this research. Simulation timestep was set to be 12 per hour (i.e. 5 minute). Tests were conducted with more timesteps per hour and the results were virtually identical, with a penalty of much longer simulation run times (see Section 5.8.1.1).

5.2.2 DesignBuilder

DesignBuilder (2011) is a commercially available software package that offers steady state load calculation using SBEM (Simplified Building Energy Model) for code compliance as well as detailed dynamic thermal simulations, for which it uses the EnergyPlus simulation engine. DesignBuilder provides a user friendly graphical user interface (GUI), enabling easy and accurate input of building geometry, construction materials, gains and profiles. The main advantage of using DesignBuilder for this research was the ability to export the EnergyPlus IDF, which could then be modified using a text editor or the EnergyPlus IDF Editor. The IDF could then be used in batch controlled simulations as described in the next section. DesignBuilder version 2.3.5, released in 2010, was used to construct the dwelling simulation models.

5.2.3 jEPlus

The research was not only concerned with the effect of single interventions, but also combined interventions (Section 4.9). The resulting tens of thousands of intervention combinations for the range of dwelling types, orientations and occupancy profiles, meant that a control method was required to automate the parametric simulation process. A Java based parametric simulation tool, jEPlus, has been developed within the IESD by Dr. Yi Zhang (Zhang, 2009). jEPlus automates batch processing through a parameter tree structure to change model construction properties and settings in EnergyPlus simulations. Single parameters, such as orientation or wall solar absorptivity, can be replaced by a search string, which allows alternative values to be specified for each simulation. More complex changes, for example different wall constructions, can be made by replacing sections of the IDF file using jEPlus to control the EP-Macro Program in EnergyPlus (U.S. Department of Energy, 2011a). The parametric simulations can also be run automatically for different weather files if required.

jEPlus also takes advantage of available parallel processing capability, allowing simultaneous EnergyPlus simulations depending on the number of computer cores or threads available. Typical modern desktop computers may have dual core or quad core processors, with up to 2 threads per core. Shorter parametric test runs were carried out using an 8-core Mac Pro computer, running 16 threads. Larger runs were carried out using the IESD cluster, allowing up to 256 simultaneous simulations.

A parameter tree was constructed for each dwelling type. Figure 5.2 shows an example parameter tree structure, in this case for the semi-detached house model (adapted from Zhang and Korolija, 2010). To model the effect of all the selected combinations of interventions for the two occupancy profiles and four orientations resulted in 16,384 simulations for the semi-detached house and the same number for the flats. The terraced houses required 12,288 simulations (no cavity wall insulation intervention) and the detached house 2,048 simulations (no insulation interventions), producing a total of 47,104 simulations. The simulations were carried out using the 2003 weather file to produce the overheating results and repeated using the CIBSE TRY weather file for annual space heating energy use, a total of 94,208 simulations.

The simulations were carried out in batches for one orientation and occupancy profile at a time, which took between 1 and 5 hours per batch on the DMU cluster, depending on the dwelling type. For comparison, the same single orientation batch would have taken up to a month on a standard dual core PC. Allowing for set-up time and other jobs in the queue for the cluster, it took approximately two weeks to complete one weather file simulation run.

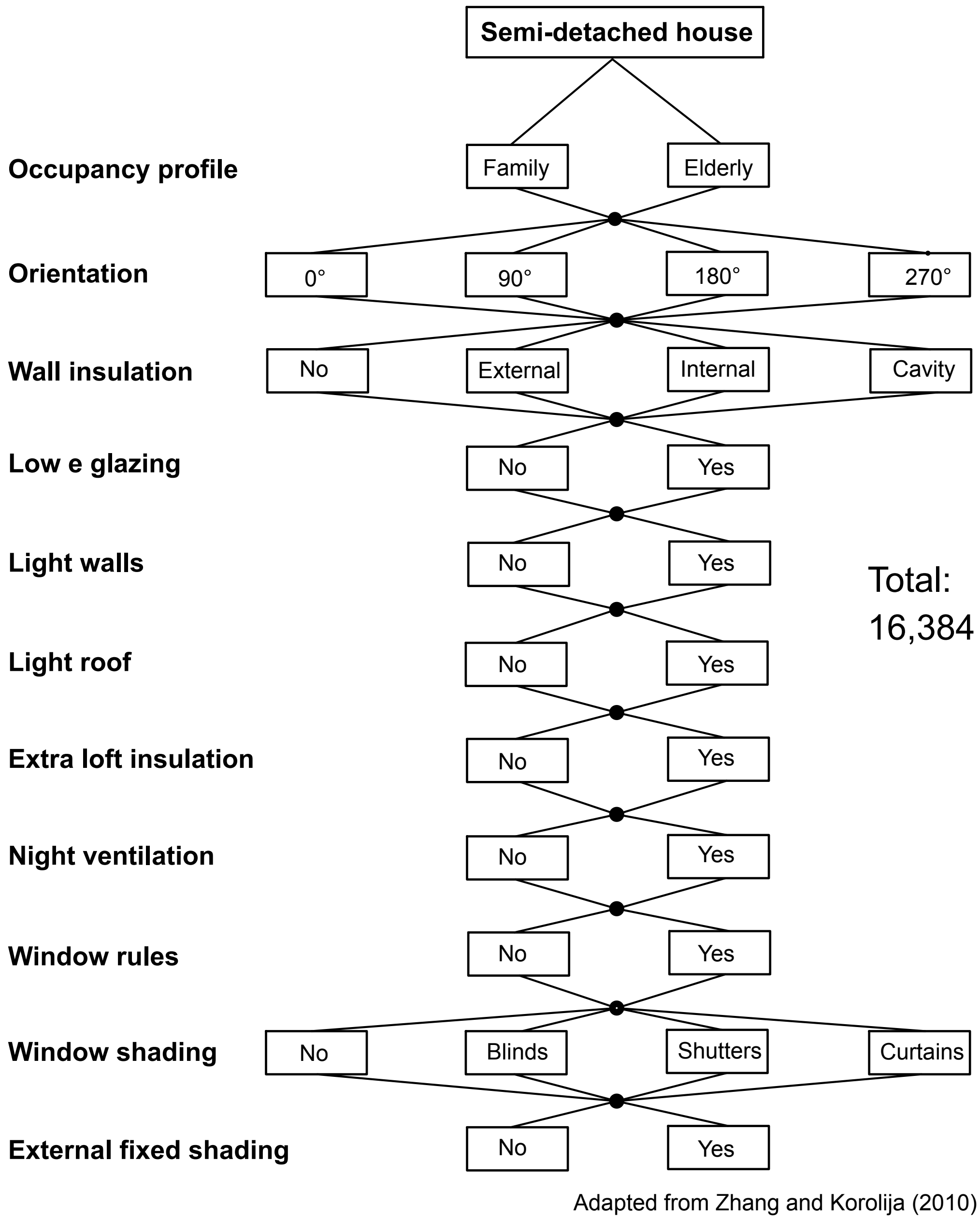

Figure 5.2 – Example parameter tree - semi-detached house

For the overheating simulations each results file included the number of degree hours over the threshold temperatures for the living room and main bedroom, calculated within EnergyPlus using the EMS facility (Section 5.4.2). Also, each results file for the heating energy use simulations included the annual space heating energy use for each room. jEPlus has built-in post processing tools to collect the individual results from each output file within a batch of simulations and collate them into a single spreadsheet. The individual output files are also stored for later analysis if required.

5.3 Ventilation control

Figure 5.3 – Different windows in similar houses

No two houses - even of the same type - will have the same openable window area. For example, in the majority of cases the original sash windows installed in 19th Century terraced houses will have been replaced several times over the years. The range of replacement window options means that the openable window area and type of opening (top hung, side hung, bottom hung, sliding or sash) will vary greatly between houses. British Standard 5925:1991 (BSI, 1991) recommends that the openable area should be at least one twentieth of the room floor area. However, a survey of semi-detached properties of the same type in one street near Milton Keynes (Figure 5.3) showed that in reality there are large variations from house to house.

The type of windows can also have a large impact on the amount of ventilation. Research by Coley (2008) highlights the issues surrounding modelling window opening and how IES software, using the MacroFlo bulk airflow simulation program (IES, 2011b) could overestimate ventilation by up to 5 times by using normal methods for top hung windows.

DesignBuilder provides two methods of setting up the ventilation calculation method used in EnergyPlus simulations: calculated ventilation and scheduled ventilation. The calculated ventilation option requires knowledge of the maximum openable area of each external opening and detailed information about cracks in the building envelope, as well as wind pressure coefficient data for the building surfaces. EnergyPlus can then use the airflow network program to calculate infiltration and ventilation air changes including the effects of buoyancy and wind. However, although this method could potentially give very accurate results, without detailed knowledge of each building there is a danger that misleading results could be generated.

The alternative approach to modelling the ventilation and infiltration is to use the scheduled ventilation option, in which ventilation air change rates and background infiltration are set for each zone. EnergyPlus can then calculate zone air mixing according to internal opening settings. The DesignBuilder user documentation (DesignBuilder, 2011) recommends using the scheduled ventilation option if the natural ventilation and infiltration rates can be reasonably estimated. The scheduled ventilation option also has the advantage of shorter simulation times, being approximately four times quicker than the calculated option for the dwelling models.

The UK Government's Standard Assessment Procedure (SAP) for Energy Rating of Dwellings (Building Research Establishment, 2010) provides effective air change rates (ACH) for dwellings in hot weather, derived from procedures in BS 5925 (BSI, 1991). For rooms in two storey dwellings, where cross ventilation is possible, the maximum effective air change rate when windows are fully open is 8 ACH and where cross ventilation is not possible the maximum is 5 ACH. For single storey dwellings, such as flats, the maximum ventilation rate is 6 ACH for rooms with cross ventilation and 4 ACH for rooms with no cross ventilation. These values are not linked to wind speed and are the assumed maximum air change rates with fully open windows. In line with assumptions used in the SAP rating procedure internal doors were left open during the daytime, with the exception of bathroom doors and kitchen doors when cooking was taking place. Bedroom doors were assumed to be closed at night.

The scheduled ventilation method was adopted for this research using the air change rates detailed above. For the base case dwellings ventilation due to window opening commenced when the room operative temperature reached 22 °C and increased linearly until reaching the maximum value by 28 °C (see Section 4.7.2). However, EnergyPlus would not allow this strategy using built-in controls and a different method was required to control ventilation, which is described in the next section.

5.4 Energy Management System (EMS)

EnergyPlus provides a means for developing customised control of some routines by writing small programs using the Energy Management System (EMS), which uses EnergyPlus Runtime Language (Erl). The EMS documentation can be downloaded from the U.S. Department of Energy (2010). In this research EMS routines were used to customise ventilation control and to provide direct output of degree hours over threshold temperatures to reduce post processing.

5.4.1 EMS for ventilation control

The options for controlling ventilation either by window opening or air change rate in EnergyPlus are limited. It is possible to control ventilation by temperature, however by default ventilation is not allowed if the outside air temperature exceeds the inside air temperature. It is not possible to override this control in the standard EnergyPlus IDF. The base case and modified ventilation control strategies discussed in Sections 4.7 and 5.3 required a more sophisticated simulation control system, which the EMS allows.

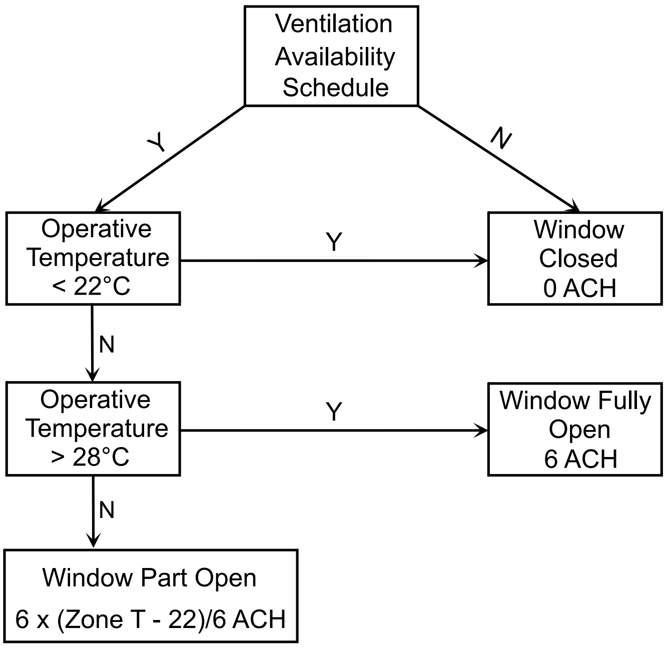

Figure 5.4 – Example EMS ventilation control flowchart

The EMS control works by setting up sensors (here using the zone operative temperature and ventilation availability schedules) and writing routines to control actuators (the natural ventilation air change rate). A flow diagram of the EMS routines is shown in Figure 5.4 for a living room in one of the flats for the default ventilation control strategy. Appendix C contains examples of the EMS program code.

5.4.2 EMS for degree hours output

The EMS facility was also used to reduce post processing of the simulation results. To determine the number of degree hours over the threshold temperatures (Section 2.4.1) would normally require output of hourly room operative temperatures for each simulation, which could then be processed through a spreadsheet utility (e.g. Excel) to calculate the number of degree hours.

A series of routines were written in EMS to calculate the heat wave period overheating degree hours for the living room and main bedroom, which could then be collected for each simulation in a jEPlus simulation run and output in a single spreadsheet. The individual hourly temperature results were stored for each simulation for later analysis if required. This greatly reduced post-processing and time required for each simulation.

5.5 Constructing the 2003 EnergyPlus weather file

The 2003 heat wave was selected for the simulation modelling presented in this research. The weather file was produced using weather data for London Heathrow, which was obtained from the UK Meteorological Office via the British Atmospheric Data Centre (UK Meteorological Office, 2011c). However, the weather data did not exist in a format ready for use in EnergyPlus simulations and several of the required weather variables were missing. Some could be calculated from other weather station readings, but the main issue was the lack of solar radiation measurements. There were two possible solutions to this problem, either the solar data could be approximated using cloud cover data or alternatively, actual solar data from a nearby weather station could be used. Following discussions with simulation weather data experts in the IESD (Professor Vic Hanby and Dr. Stefan Smith) the latter approach was adopted to construct the 2003 weather file, using solar data from the London Weather Centre.

The methods used to construct the simulation weather files are detailed in Appendix D. Table 5.1 contains the key weather data, including temperatures and solar radiation data, for each day of the 2003 heat wave.

		Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9
Dry bulb temp (°C)	Max	31.6	31.3	35.2	29.7	30.7	34.8	37.3	33.1	29.6
	Min	16.7	19.0	21.7	18.2	18.9	18.5	20.2	20.0	18.9
Relative humidity (%)	Max	83	86	80	88	85	89	83	86	86
	Min	41	37	31	45	45	28	18	38	49
Atmospheric pressure (kPa)	Ave	102.1	102.0	101.7	101.8	101.7	101.6	101.4	101.5	101.7
Direct normal radiation (Wh/m^2)	Max	686	652	718	649	632	785	718	641	704
Diffuse horizontal radiation (Wh/m^2)	Max	208	296	227	290	374	167	197	342	294
Wind speed (ms^{-1})	Max	6.7	6.7	5.7	5.7	4.6	4.1	9.3	6.2	4.6
	Min	1.0	2.1	1.5	2.1	1.0	0.5	0	2.6	1.5

Table 5.1 – August 2003 heat wave key weather variables

5.6 Simulation of space heating energy use

Interventions that reduce solar gains and which are permanent alterations to the building fabric will increase annual space heating energy use, through the loss of beneficial gains during the heating seasons. Conversely, some of the other modelled interventions, such as adding insulation, will reduce space heating energy use. Other interventions that are behavioural, which includes ventilation changes (window rules and night ventilation) or closing curtains, blinds and shutters, will have no effect on energy use if they are not employed during the heating season.

To quantify the impact of the interventions on heating energy use the ideal loads air system was used in EnergyPlus (previously known as purchased air). This avoids the need to specify air or water loops and is the simplest way to carry out loads calculations in EnergyPlus. The purchased air method was tested in a comparison of different methods for calculating heating energy use by Georgios et al. (2007) and the results were found to be in close agreement with those from ESPr simulation software.

The aim within this research was to predict the relative effect on space heating energy use of the modified dwellings compared to the base case dwellings, i.e. the percentage increase or decrease in heating energy use. The actual energy used for space heating will depend on heating system type, it's age, boiler and pump efficiency etc. A whole system efficiency of 0.65 was used to allow for these factors and a base load of 3.26 kWh/m^2 added to allow for pump energy use. These values were selected based on a BRE profile for a domestic hot water radiator system in the DesignBuilder database.

CIBSE (2006) provides winter thermal comfort operative temperatures for different rooms in dwellings, with living rooms in the range 22 °C - 23 °C, bedrooms 17 °C - 19 °C and bathrooms 20 °C - 22 °C. SAP 2009 (Building Research Establishment, 2010) provides heating set point temperatures for use in calculating dwelling energy use. The temperatures are split into two categories, living areas and other areas. The living area temperature is 21 °C, whereas the other areas temperature is calculated by subtracting a figure of half the heat loss perimeter of the room from 21 °C, with an upper limit value of 6.0m for the heat loss perimeter. The minimum temperature for other areas is therefore 18 °C, but could be as high as 20 °C for a room with a small (2.0m) external wall. Hacker et al. (2008) used the 21 °C temperature for living areas in their energy use simulations and a temperature of 19 °C for bedrooms, consistent with the SAP figures. A higher temperature of 22 °C was specified for bathrooms. These were the set point temperatures adopted for the heating energy use simulations in this research.

CIBSE (2006) states that for given clothing and activity levels the thermal environments preferred by elderly occupants are similar to those for younger people, therefore the same heating set points were used for both occupancy profiles. The family occupancy assumed that the heating was on from 0700 - 0900 and again from 1600 - 2300, Monday to Friday, and 0700 - 2300 at weekends. The elderly profile assumes the heating is on from 0700 - 2300 all week.

This research is mainly concerned with the relative effects and the percentage increase or decrease in heating energy use through the addition of interventions. Although annual heating energy use is likely to reduce under a future warmer climate, the immediate concern will be for current not future energy use. Therefore the current CIBSE London Heathrow TRY weather file was used for the heating energy use simulations.

In the case of external fixed shading where awnings were used for ground floor east and west facing windows, these were assumed to be retracted during the heating season. Other fixed shading devices were assumed to be permanent building fixtures, in place all year round, though removable devices could be specified that would not affect winter energy use.

5.7 Modelling validation

One of the main concerns regarding the use of simulation software is the ability to accurately predict real world building performance. ASHRAE (2009) lists three ways to evaluate the accuracy of simulation programs: *empirical validation*, where simulated results are compared to monitored data from real buildings; *analytical verification*, where the simulation outputs are compared to results from a known analytical solution and *comparative testing*, which compares the current software to previous versions or to other programs. Lomas et al. (1994) devised a series of blind tests to validate the main thermal simulation programs available at the time, identifying some significant variations between the programs.

Various tests have been carried out on EnergyPlus and its predecessors (DOE-2 and BLAST) over the years. Each version of EnergyPlus goes through a series of validation tests (U.S. Department of Energy, 2012), which include analytical HVAC and building fabric tests, comparative testing, including ANSI/ASHRAE Standard 140 (BESTest) (U.S. Department of Energy, 2011b) and other release and executable tests.

Neymark and Judkoff (2002) provide a summary of empirical validation work from around the world, including tests conducted in the UK for the International Energy Agency. Empirical validation is difficult, because to get meaningful results for comparison the simulation input parameters, including construction materials, dimensions, internal gains and local weather, must match those of the real building under test. Doing this for existing buildings, where much of the fabric of the building is hidden from view, means a certain amount of educated guesswork to construct the simulation model. During the test period accurate records are required at hourly intervals (at least) to provide operational simulation inputs. These include recording the number of people in each room at any time, any gains from equipment and lighting and the operation of openings (windows and doors) to enable calculation of ventilation air exchange rates.

A small empirical validation exercise was conducted using a studio apartment in Leicester to provide confidence in the modelling methodology and the accuracy of EnergyPlus in predicting room temperatures. The results from the EnergyPlus simulation were in reasonable agreement with the monitored temperature. The modelling details and results for the validation exercise are contained in Appendix E.

5.7.1 Comparison with 2003 monitored dwellings

Nine dwellings were monitored during the 2003 heat wave by Wright et al. (2005), four in Manchester and five in London. Of the London dwellings, none were an

	Room	Min (°C)	Mean (°C)	Max (°C)
Monitored 1960 flat (occupancy unknown)	Living	26.7	30.3	37.4
	Bedroom	26.0	29.3	39.2
Simulated 1960s top floor flat (family occupancy)	Living	27.3	31.7	37.7
	Bedroom	25.4	30.8	37.4
Monitored solid wall semi-detached house (occupancy unknown)	Living	24.0	27.0	31.9
	Bedroom	26.7	28.4	31.9
Simulated 19th century end-terraced house (family occupancy)	Living	25.8	28.2	32.6
	Bedroom	24.8	28.5	33.0

Table 5.2 – Comparison between modelled results and monitored dwellings (Wright et al., 2005)

exact match for any of the modelled dwellings, although two were similar. One was a 4-bedroom semi-detached house constructed in the 1930s, with the living room east-facing. It had solid brick wall construction and 90% double-glazing and was therefore similar to the modelled end-terraced dwelling. The main difference was the lack of any loft insulation and it is also not known what the room layout was (in particular, which way the bedroom was oriented). The other four London dwellings were all flats, one of which was constructed in 1960. It had concrete construction with cladding panels and a brick interior wall with no cavity insulation. It had no double-glazing and the living room was east-facing, though it is not known on which storey the flat was located.

The minimum, mean and maximum temperatures were recorded during the 2003 heat wave in the living room and a bedroom for each of the monitored dwellings, using i-Button loggers (Maxim, 2012) which have a stated accuracy of ±0.5 °C. Monitoring for the London dwellings did not start until the 7th August and ran to the 13th (Table 5.2). Simulation results (also for the period 7th-13th August) are included in Table 5.2 for the end-terraced house with loft insulation set to zero and the top floor 1960s flat with single-glazing replacing the default model double-glazing. The monitored temperatures demonstrate how the overheating in the 1960 flat was considerably greater than that in the solid wall semi-detached house and also that the results from the simulation models mirror these differences and are in reasonable agreement with monitored dwellings of similar type and construction.

5.8 Uncertainty and sensitivity testing

Uncertainty relates to the possible variability within modelling input parameters. For example, the materials with which bricks are made can lead to a wide range of conductivity, specific heat capacity, density and solar absorptivity values. Sensitive parameters are those that have the greatest influence on the simulation outputs, but sensitive parameter values may be known to a high degree of accuracy. The most important parameters are therefore those that have a high degree of uncertainty and have the greatest influence on the modelling outputs (Macdonald et al., 1999).

Even in a relatively simple simulation model, such as a naturally ventilated dwelling, there are many inputs and software settings that could have alternative values. This is particularly true when modelling existing dwellings where there is a degree of uncertainty about the construction methods and materials used. The software tools have also evolved over the years and there are now many choices for calculation options, including inside and outside surface convection algorithms and simulation timestep.

Lomas and Eppel (1992) were amongst the earliest to address sensitivity analysis for DTM software tools, in this case for ESP, HTB2 and SERI-RES. They contrasted three different analysis techniques: differential sensitivity analysis (DSA), Monte Carlo analysis (MCA) and stochastic sensitivity analysis (SSA). During the course of their testing, Lomas and Eppel investigated the sensitivity of simulation outputs (air temperature and daily energy use in kWh) to uncertainties in thermophysical properties of construction materials and a range of other model inputs, including thermostat set-point, glazing, zone volume, surface absorptivity and casual gains. MCA cannot be used for assessing individual input uncertainties and SSA cannot be used where scheduled input parameters are included (e.g. casual gains). The ranking orders using DSA were found to be similar for all three programs, with thermostat set-point having the biggest effect on the results, followed by glazing U-value and grouped conductivities of construction materials. Macdonald (2002) carried out DSA tests on a model of an office building and identified the four most sensitive parameters to be the conductivity of the external wall insulation, the ambient temperature, equipment casual gains and the infiltration rate.

This research is concerned primarily with the relative effects of retrofit interventions. Whilst it is desirable to predict the internal temperatures and hence overheating degree hours as accurately as possible, it is the change in degree hours between the base case dwellings and the versions with interventions that is more important. Whilst every effort was made to accurately set the construction materials, internal gains and occupancy profiles within the simulation models, there will still be variations between the models and their real world counterparts.

5.8.1 Sensitivity analysis

It was beyond the scope of this PhD to carry out a full uncertainty and sensitivity analysis on all the simulation inputs and settings. However, some sensitivity analyses were carried out and these are detailed below.

5.8.1.1 Simulation timestep

In total there were 47,104 simulations for the heat wave period and the same number of annual simulations were carried out to determine heating energy use. The Institute cluster computer is a shared facility with many users, therefore the time taken for each simulation was a significant factor. The simulation timestep sets the number of iterations per hour and must be a number evenly divisible into 60. The minimum recommended value is 6 for CTF simulations, however it was found that under certain circumstances (low levels of loft insulation), simulations could occasionally fail at timesteps below 12. Increased timesteps come with the penalty of longer simulation run times, therefore tests were conducted to assess the impact of simulation timestep on the results.

	Timesteps per hour				
	6	**12**	20	30	60
Simulation run time (s):	130	**226**	325	447	789
	Total overheating degree hours				
Base case*	836	**840**	842	842	844
External wall insulation	829	**835**	836	838	839
Internal wall insulation	873	**876**	879	880	881
Cavity wall insulation	868	**873**	875	876	877
Low e triple glazing	687	**691**	692	693	694
Light walls	631	**635**	637	638	639
Light roof	669	**674**	675	676	677
Upgrade flat roof	819	**822**	822	823	824
Internal blinds	642	**645**	464	647	648
External shutters	491	**495**	496	497	498
Curtains	697	**700**	701	702	703
Night ventilation	708	**714**	716	717	718
Window rules	833	**838**	839	840	841
External fixed shading	525	**530**	531	531	532

* Top floor flat, front north facing, elderly occupancy

Table 5.3 – Effect of simulation timestep

Table 5.3 shows the effect of selecting timesteps from 6 (the minimum recommended) to 60 (maximum) per hour on the total number of degree hours over threshold temperatures for the top floor flat during the 2003 heat wave, assuming elderly occupancy. The simulation run time (seconds) is shown for each timestep value for the base case simulation. The results demonstrate that changing the timestep has very little effect on the results and that increasing the number of timesteps has a significant effect on simulation run time. The decision was made to use the minimum timestep value that produced stable simulations for all cases, which was 12 timesteps per hour.

5.8.1.2 Infiltration

The terraced houses have a background infiltration value of 0.7 ACH (see Section 3.3.1). The value may be less if extensive draught proofing has been carried out and for some houses the infiltration may be higher, for example if there are open fire-places. The effect of specifying a lower (0.5 ACH) and a higher (1.0 ACH) infiltration value for the end-terraced house was tested and the results are in Table 5.4.

	Degree hours over 28 °C (and reduction from base case) for each infiltration value:					
	0.5 ACH		**0.7 ACH**		1.0 ACH	
Intervention (ranked):						
Light walls	61	(-65%)	**60**	**(-64%)**	59	(-64%)
External wall insulation	76	(-56%)	**76**	**(-55%)**	76	(-53%)
Internal wall insulation	119	(-32%)	**119**	**(-29%)**	119	(-27%)
External shutters	129	(-26%)	**126**	**(-25%)**	122	(-25%)
Window rules	131	(-25%)	**127**	**(-24%)**	123	(-24%)
Light roof	133	(-24%)	**130**	**(-23%)**	127	(-22%)
Night ventilation	140	(-20%)	**138**	**(-18%)**	135	(-17%)
External fixed shading	147	(-16%)	**143**	**(-15%)**	137	(-15%)
Internal blinds	148	(-15%)	**144**	**(-14%)**	139	(-14%)
Low e triple-glazing	150	(-14%)	**146**	**(-13%)**	141	(-13%)
Curtains	153	(-12%)	**148**	**(-12%)**	143	(-12%)
Loft insulation upgrade	168	(-3%)	**163**	**(-3%)**	157	(-3%)
Base case*	174	-	**168**	**-**	162	-

* End-terraced house living room north facing

Table 5.4 – Effect of infiltration setting

Changing the infiltration level had some effect on the results, with base case over-heating 3.6% higher when using 0.5 ACH and 3.6% lower when specifying 1.0 ACH compared to the default setting of 0.7 ACH. Solar control interventions (light walls, external shutters, internal blinds and curtains) produced similar percentage reductions for each infiltration value, whereas the effectiveness of wall insulation reduced as the infiltration level increased. However, the intervention ranking order was the same for each infiltration value.

5.8.1.3 Construction materials

Limited sensitivity tests were also carried out on some of the fabric material properties, including brick and plaster conductivity, density and specific heat capacity values for the solid walled end-terraced house. The effect on the results (degree hours over threshold temperatures) was small and importantly the ranking order of the interventions was not changed.

Further uncertainty and sensitivity analysis is recommended for future research (Section 10.4).

5.9 Summary

This chapter has discussed the options for modelling software and the reasons for choosing DesignBuilder/EnergyPlus to carry out the dynamic thermal modelling. The use of jEPlus to control the parametric simulations was described and modifications to control EnergyPlus using EMS routines were presented. The accuracy of EnergyPlus simulations was discussed, including modelling validation and sensitivity testing.

Chapter 6

Results 1: Base case dwellings

6.1 Foreword

Chapters 2 to 5 provided the background to the research project and detailed the methodology behind the modelling process. This chapter compares the base case performance of each dwelling for the different orientations and occupancy profiles, identifying those which are prone to the greatest overheating risk and comparing the space heating energy use. Chapter 7 analyses the effect of the modelled interventions on one dwelling type in detail (the top floor flat) and Chapter 8 presents the simulation results for the other dwelling types. The results are then compared across the dwelling types and discussed in Chapter 9.

6.2 Base case simulation results

The four dwelling models were simulated in EnergyPlus using the methodology described in Chapter 5. The simulation output provided the number of degree hours over the CIBSE comfort threshold temperatures (28 °C for the living room and 26 °C for the main bedroom) for occupied periods during the August 2003 heat wave. The simulations were then repeated for a whole year to determine annual space heating energy use using the current CIBSE London Heathrow TRY weather file. Results were produced for the ground, mid and top floor 1960s flats, the nineteenth century end and mid-terraced houses, the 1930s semi-detached house and the modern detached house. Each dwelling type was modelled for 2 occupancy profiles and 4 orientations, producing 56 sets of simulation results.

Results are presented for the living room and main bedroom combined (Figure 6.1), to provide an indication of the total overheating exposure for occupied periods during the heat wave. Figures 6.2 and 6.3 present the individual results for the living rooms and main bedrooms. In each case the orientation (A-D) refers to the direction the front of the dwelling faces (see Section 3.3 for the dwelling floor plans), with the direction the individual room windows face indicated in Figures 6.2 and 6.3. Space heating energy use simulation results are presented in Section 6.2.4.

6.2.1 Effect of dwelling type on overheating

The top floor flat was found to be the worst performing dwelling type for total overheating, with the mid floor flat and the detached house experiencing similar high levels of overheating. The semi-detached house experienced less than half the overheating exposure of the worst performing dwellings, whilst the terraced houses and ground floor flat experienced the lowest total overheating of the modelled dwellings.

Total overheating degree hours for elderly occupants ranged from 99 in the north-facing mid-terraced house to 897 in the east-facing top floor flat (living room and main bedroom west-facing). Figure 6.4 shows the living room temperatures in these two cases for the 2003 heat wave period. The elderly occupants in the top floor flat experienced a peak operative temperature of 38.8 °C in the top floor flat compared to 30.5 °C in the mid-terraced house. For family occupants the lowest overheating (55 degree hours) was in the ground floor flat with north-facing living room and

Figure 6.1 – Base case dwellings total overheating

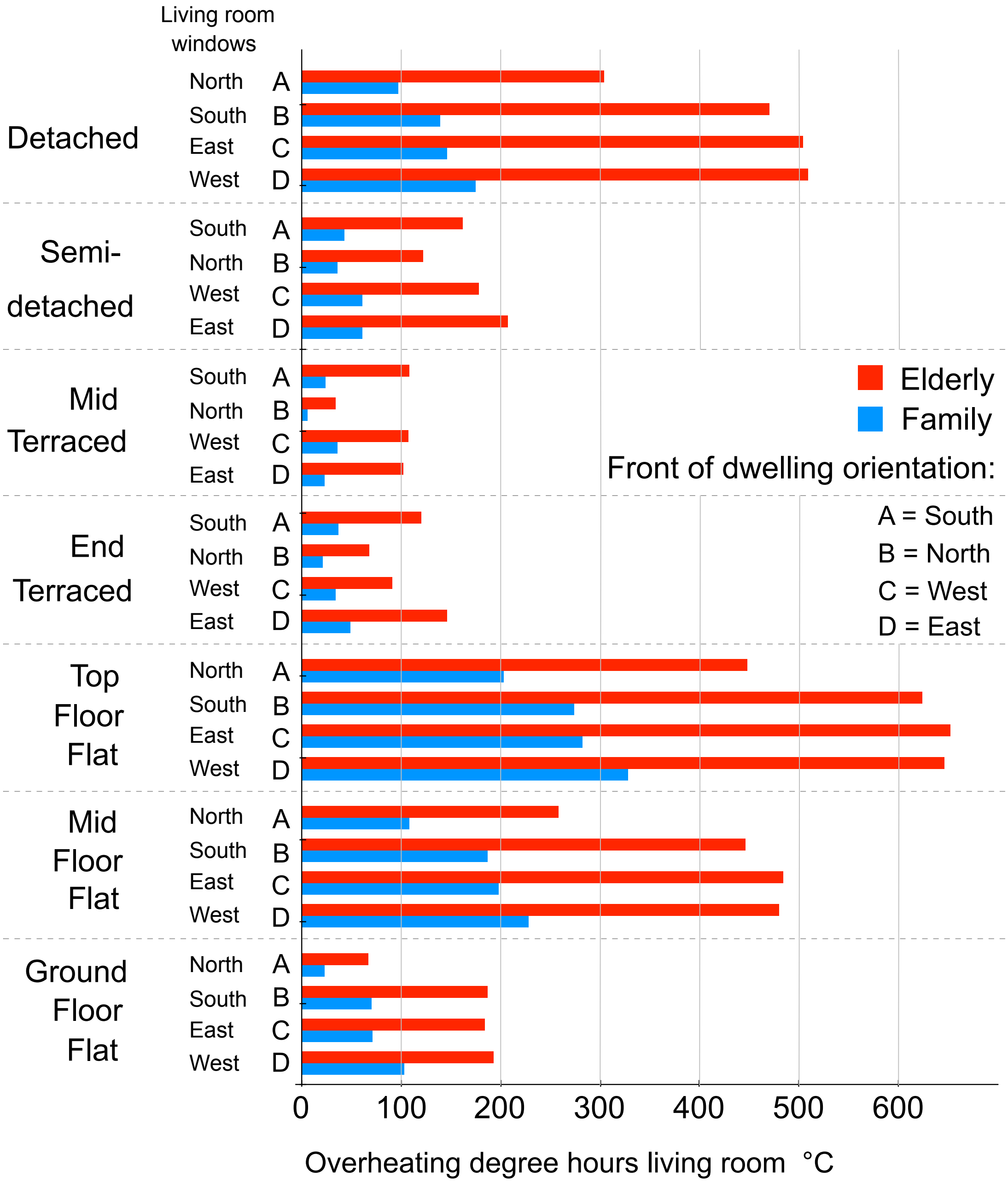

Figure 6.2 – Base case dwellings living room overheating

Figure 6.3 – Base case dwellings main bedroom overheating

main bedroom windows and the highest overheating again in the top floor flat with west-facing windows (566 degree hours). Therefore elderly occupants experienced up to 8.5 times and family occupants up to 10.3 times the total overheating exposure, depending on dwelling type and orientation.

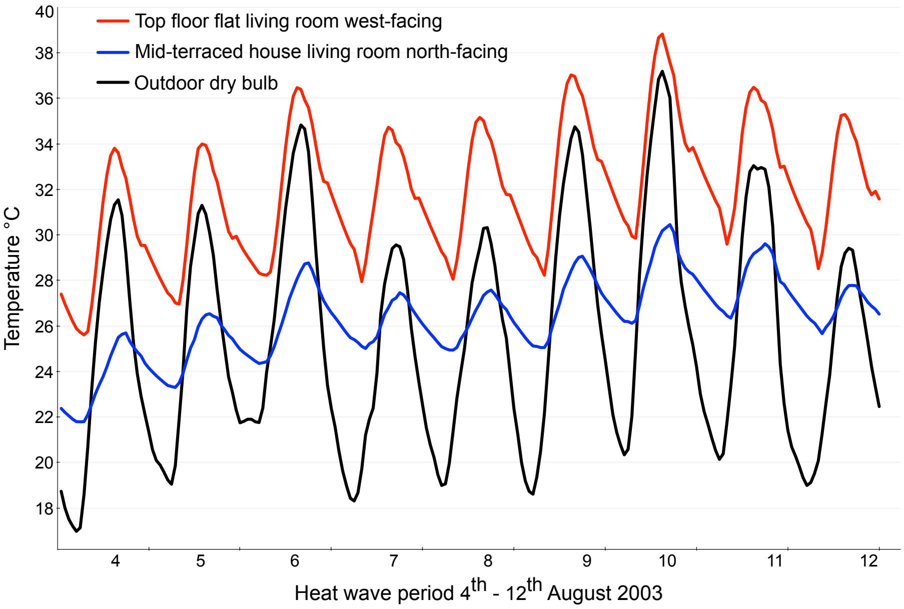

Figure 6.4 – Comparison of living room temperatures during the 2003 heat wave

6.2.2 Effect of orientation on overheating

Comparing the effect of changing the orientation for each dwelling type was not straightforward. Each dwelling was rotated such that the front faced south, north, west and east. However, each dwelling type has different room layouts (see the floor plans in Section 3.3). For example, the living room is at the front in the terraced and semi-detached houses, but at the rear in the others. In the cases of the detached and semi-detached houses the main bedroom is at the front and in the others at the rear. Therefore in the flats and the semi-detached house the living room and main bedroom have windows facing the same direction, whereas they face opposite directions in the terraced and detached houses. Some rooms also have additional (unglazed) external walls. The end-terraced house has second external walls for both the living room and main bedroom, as does the detached house. The bedrooms in each flat also have a second (end) external unglazed wall.

Flats

Orientations with east and west-facing windows recorded the highest overheating degree hours. Orientation D for the top floor flat with elderly occupants (Figure 6.1) experienced the greatest total overheating (897 degree hours). In this case the living room and main bedroom windows were west-facing and the second main bedroom external wall was south-facing. The west-facing walls and windows were exposed to large amounts of solar radiation during the afternoon and early evening and the south-facing wall also had significant solar exposure during the day. The mid (1st) floor flat experienced between 17% and 35% less total overheating than the top floor flat, when comparing the same orientations.

The position of the flat in the block also had a marked effect on overheating exposure. In the worst case (top floor, living room and main bedroom west-facing) elderly residents experienced over 8 times the total overheating exposure of the best case (ground floor, living room and main bedroom north-facing). In the mid floor flat with south, east or west-facing windows the overheating exposure was greater than the lowest overheating case for the top floor flat, where the living room and main bedroom windows faced north.

When considering living room and main bedroom overheating independently for the flats, orientation D was still the worst performing for most cases, with the exception of mid and top floor living rooms with elderly occupancy, where east-facing windows resulted in slightly higher overheating (Figure 6.2). The solar gain through the windows in the mornings was significant for the elderly residents, but not as important for the family who were out of the house during the daytime.

Although living room overheating was significantly higher in the top floor flat than in the mid floor flat, main bedroom overheating was similar and slightly higher in the mid floor flat. The poorly insulated flat roof allowed some of the heat in the top floor flat bedrooms to dissipate at night.

Terraced houses

Overheating in the end-terraced house was higher than in the mid-terraced house for three of the orientations (front south, north and east) as a result of solar heat gains through the solid end wall. When the front of the end-terraced house was west-facing, the end wall was north-facing and therefore not exposed to direct solar radiation during the daytime. For this orientation overheating in the mid-terraced house was higher. The lowest total overheating for elderly occupants amongst all the dwelling types (99 degree hours) was in the north-facing mid-terraced house, where the living room had north-facing windows and the main bedroom had south-facing windows.

For both individual rooms and total overheating exposure in the end-terraced house the highest results for both occupancy profiles occurred when the front was east-facing. Although the living room received no direct solar radiation through the windows during the afternoon, the end wall was south-facing and the windows at the rear of the house (including the main bedroom) were west-facing.

The lack of a solid end wall in the mid-terraced house produced different results, which varied depending on room type and occupancy. Living room overheating was greatest for elderly occupants when the windows were south-facing. For family occupants, who did not use the living room until the evening, the west-facing orientation produced the highest overheating. Main bedroom overheating was greatest (and similar) for east/west orientations, with east-facing bedroom windows resulting in slightly higher overheating for elderly occupants and west-facing windows being the worst for family occupants. Total overheating was greatest in the mid-terraced house when the front was west-facing for both occupancy profiles.

Semi-detached house

Overheating in the semi-detached house was higher than in the terraced houses and the ground floor flat, but still significantly lower than the worst performing dwellings (detached house and the mid and top floor flats). The living room and main bedroom are both at the front of the semi-detached house and for this dwelling the same orientation (front east-facing) resulted in the highest overheating both for individual rooms and total overheating. When the front was east-facing the end wall was south-facing (party wall between the houses north-facing) and the rear of the house west-facing. The dining room patio doors (at the rear) provide a large glazed area which contributed significant solar heat gains during the afternoon and the open internal doorways allowed transfer of these heat gains through the house.

The lowest overheating, for both occupancy profiles, occurred when the front was north-facing. In this case the living room and main bedroom received little direct solar radiation and the neighbouring (attached) house protected the modelled house from afternoon solar heat gains from the west.

Detached house

The detached house was one of the worst performing dwellings for overheating, being comparable to the mid floor flat and only slightly better than the top floor flat. Living room overheating for both occupancy profiles was highest when the front of the house was east-facing and the living room windows (at the rear) were west-facing. For this orientation the glazing solar heat gains were high in the afternoon and the living room second wall was south-facing. The lowest living room overheating was when the windows were north-facing. The main bedroom overheating was greatest when the front of the house (and main bedroom windows) were west-facing, which also meant that the other main bedroom external wall was south-facing. Again, the lowest overheating was observed when the bedroom windows were north-facing.

The living room and main bedroom are on opposite sides of the house and total overheating was greatest (and very similar) when the front was east or west-facing and over 50% higher than the lowest overheating, when the front was south-facing (living room windows north-facing).

6.2.3 Effect of occupancy type on overheating

The elderly profile assumes occupancy by vulnerable or infirm residents who occupy the dwellings all the time and are therefore at home during the afternoon, the hottest part of the day during a heat wave. Their overheating exposure is therefore significantly higher than the typical family occupants, who are assumed to be out of the dwellings during the daytime. Living room overheating exposure for elderly occupants was found to be up to 5.7 times higher than for family occupants (north-facing mid-terraced house), although more typically 2 to 3 times higher.

The main bedroom occupied periods for the family adults and the elderly couple were similar. However, higher heat gains resulting from daytime occupancy built up to produce higher main bedroom overheating (up to 1.2 times higher) for the elderly occupants. Figure 6.5 shows how the main bedroom temperature was higher during the daytime for the elderly occupancy profile, which resulted in slightly higher temperatures during the night.

The total overheating exposure, combining occupied periods in the living room and main bedroom, was typically around double for elderly occupants. For example, elderly occupants in the detached house with a south-facing living room experienced 2.4 times the total overheating exposure of family occupants in the same house.

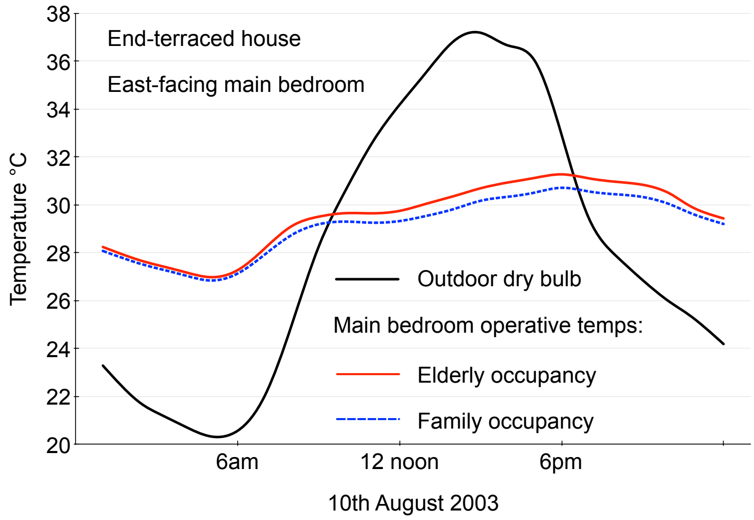

Figure 6.5 – Effect of occupancy on main bedroom temperature

6.2.4 Space heating energy use

		Annual space heating energy use (kWh/m^2/yr)			
		Orientation: front of dwelling facing:			
Dwelling type	Occupancy	North	South	East	West
End-terraced	Family	153	151	147	158
	Elderly	197	195	190	203
Mid-terraced	Family	131	126	130	129
	Elderly	170	163	168	166
Semi-detached	Family	112	118	113	119
	Elderly	133	140	135	142
Ground floor flat	Family	72	76	75	77
	Elderly	88	93	91	94
Mid (1st) floor flat	Family	63	66	67	69
	Elderly	74	77	77	81
Top floor flat	Family	81	84	84	86
	Elderly	96	99	99	102
Detached	Family	38	41	42	42
	Elderly	53	56	56	57

Table 6.1 – Base case dwellings space heating energy use

Table 6.1 contains the annual space heating energy use simulation results for each dwelling. Energy use per unit area was lowest in the modern highly insulated detached house and highest in the Victorian end-terraced house, with uninsulated solid brick walls. Elderly occupants were assumed to heat their dwellings during the daytime, resulting in greater energy use.

Flats

The ground floor flat used more heating energy than the first floor flat due to losses through the uninsulated ground floor. The mid floor flat used the least energy of all three due to the occupied spaces above and below, whilst the top floor flat had the highest energy use of the three flats due to losses through the poorly insulated flat roof. Elderly occupants, in the flats during the daytime, used between 18% and 22% more heating energy than family occupants. In each case (ground, mid and top floor) the lowest energy use was recorded when the front of the block was north-facing. For this orientation the living room and main bedroom had south-facing windows, which benefitted from solar heat gains throughout the daytime. The highest energy use (6-10% greater) occurred when the front of the block was west-facing, in which case the living room and main bedroom were east-facing. For this orientation the end wall of the block, which forms the second external wall to both bedrooms, was north-facing and therefore not receiving solar radiation.

Terraced houses

The much larger (uninsulated) external wall area of the end-terraced house resulted in between 13% and 22% higher energy use than for the mid-terraced house and the energy use for elderly occupants was around 30% higher than for family occupants for both types of terraced house. For the end-terraced house the lowest energy use occurred when the front faced east, in which case the end wall faced south and was able to absorb solar heat gains throughout the day. This resulted in around 7% less energy use than the front west-facing orientation, where the end wall was north-facing.

In the case of the mid-terraced house there is no end external wall and the front north-facing orientation used the most heating energy, being approximately 4% higher than when the front was south-facing.

Semi-detached house

Elderly occupants in the semi-detached house used approximately 19% more heating energy than family occupants for each orientation. The lowest energy use occurred when the front was north-facing. In this case the living room and main bedroom bay windows had some glazed area facing east and west, the end wall faced east and the rear of the house faced south. The front west-facing orientation, where the end wall of the house was north-facing, used 6-7% more heating energy than the front north-facing orientation.

Detached house

The modern detached house used the least heating energy per square metre, but showed the largest difference in energy use between occupancy profiles, with elderly occupants using up to 39% more heating energy than family occupants. The difference in the number of occupants between the two profiles was greatest for the 4-bed detached house, with the family profile assuming 2 adults and 3 children, compared to just 2 adults in the elderly profile. Internal heat gains were therefore much lower for the elderly profile. The lowest energy use occurred when the front of the house was north-facing, in which case the living room was south-facing. The living room has a large glazed area (patio doors), which provided a significant solar heat gain benefit when south-facing during the winter. The greatest energy use, 8-11% higher, was seen when the front was west-facing, in which case the living room windows were east-facing. In the case of family occupants the front east-facing orientation also resulted in 11% higher heating energy use.

6.3 Summary

This chapter has presented the base case simulation results for each dwelling type for the two occupancy profiles and four orientations. Overheating was found to vary significantly between dwellings, with the top and mid floor flats and the detached house experiencing over double the total overheating exposure of the ground floor flat, terraced and semi-detached houses.

Dwellings with east/west orientations were found to experience the greatest total overheating, closely followed by those with south-facing living rooms. In the case of individual room overheating, living rooms with west-facing windows generally experienced the greatest overheating for family occupants, with the exception of the end-terraced house where the east-facing living room had the highest overheating. In this case the end wall of the terrace was south-facing, receiving a large amount of solar radiation during the daytime. Overheating for east-facing living rooms with elderly (daytime) occupancy was comparable to west-facing living rooms, due to solar gains through the morning.

Space heating energy use per unit area was highest in the solid wall terraced houses and lowest in the modern detached house. Energy use for elderly residents, who occupy the dwellings all the time, was up to 39% higher than for family occupants.

The top floor flat was identified as the worst performing dwelling for overheating and the next chapter looks in detail at the effect of interventions on the top floor flat. Chapter 8 then presents the simulation results for the other dwellings, before all the results are discussed and compared in Chapter 9.

Chapter 7

Results 2: Top floor flat in detail

7.1 Foreword

The previous chapter identified that top floor 1960s flats experienced the greatest overheating of the dwelling types under investigation. Purpose built flats are the most common type of dwelling in London, with those built between 1945 and 1974 being the most common in London and South East England (Section 3.2). Poorly insulated top floor flats are also identified as a particular hazard in the Housing Health and Safety Rating System (Office of the Deputy Prime Minister, 2006a). The modelled block of flats has uninsulated cavity walls in the base case construction and, in common with the semi-detached house, had the largest number of possible interventions from those considered in this research.

The effect on overheating reduction and space heating energy use of each of the interventions was modelled in turn, comparing the effect of orientation and occupancy profile. Combined interventions were then modelled and the cost of interventions introduced to the analysis to determine the most effective combined interventions for reducing overheating and space heating energy use at a given cost.

7.2 Single interventions

Table 7.1 provides a reference to the short names used for the interventions in Figures 7.1-7.3. The interventions are discussed in detail in Chapter 4.

Short name (charts)	Description
Internal blinds	Solar reflective internal blinds, closed 0900 - 1800
External shutters	Solar reflective external shutters, closed 0900 - 1800
Curtains	Medium weave curtains, closed 0900 - 1800
Low e triple glazing	Low emissivity triple glazing
External fixed shading	Fixed shading above south, east and west-facing windows
Night ventilation	Ventilation by external air to unoccupied rooms at night
Window rules	Preventing windows from opening if the outside air temperature is higher than the inside air temperature
Upgrade flat roof	Replace the flat roof with a higher insulated roof (flats only)
Loft insulation	Extra loft insulation (houses only)
Light roof	Coat the external roof surface with high performance solar reflective paint
Light walls	Coat the external walls with high performance solar reflective paint
External wall insulation	Add external wall insulation with an outer render coat to external walls
Internal wall insulation	Add internal wall insulation with a plasterboard inner layer to the inner face of external walls
Cavity wall insulation	Fill external cavity walls with blown mineral fibre insulation

Table 7.1 – Key to interventions (details in Chapter 4)

The single intervention simulations were carried out using the 2003 London Heathrow weather file to obtain overheating results for the 9-day August heat wave period. Figures 7.1 to 7.3 show the effect of each single intervention when applied to the base case model of the top floor flat, for the four orientations and two occupancy profiles. The charts show the number of degree hours over the comfort threshold temperatures during occupied periods for the living room (28 °C) and main bedroom (26 °C), and the total overheating degree hours (living room plus main bedroom).

The occupancy profiles for the living rooms in the flats differ slightly from those used in the other dwelling types. The small kitchen and lack of a separate dining room would suggest that a dining area in the living room will be used at breakfast time for both occupancy profiles.

7.2.1 Effect on overheating

7.2.1.1 Blinds, shutters and curtains

Solar heat gains through windows could be reduced by closing external shutters, internal blinds or curtains during the daytime, although there could be a need for artificial light for daytime occupancy. External shutters were far more effective because they provided a total block to direct solar radiation before it could enter the dwelling and it was the most effective single intervention for living rooms, reducing degree hours by 44% for elderly occupants in the south-facing living room. The internal blinds used in the modelling were identical in construction to the external shutters, but were less effective because some of the short wave solar radiation that has already passed through the glazing was absorbed by the blinds and re-emitted to the room as long wave radiation and by convection, adding to the room heat gains. The curtains were the least effective of the window shading interventions, allowing some transmission of the direct solar radiation as well as absorbing some solar radiation for re-emission as long wave radiation. However, curtains were still a middle ranking intervention and, because they were assumed to be an existing feature, a zero cost measure. Internal doors were assumed to be open during the daytime (except for the bathroom door and the kitchen door when cooking was taking place), allowing the transfer of heat from solar gains to distribute through

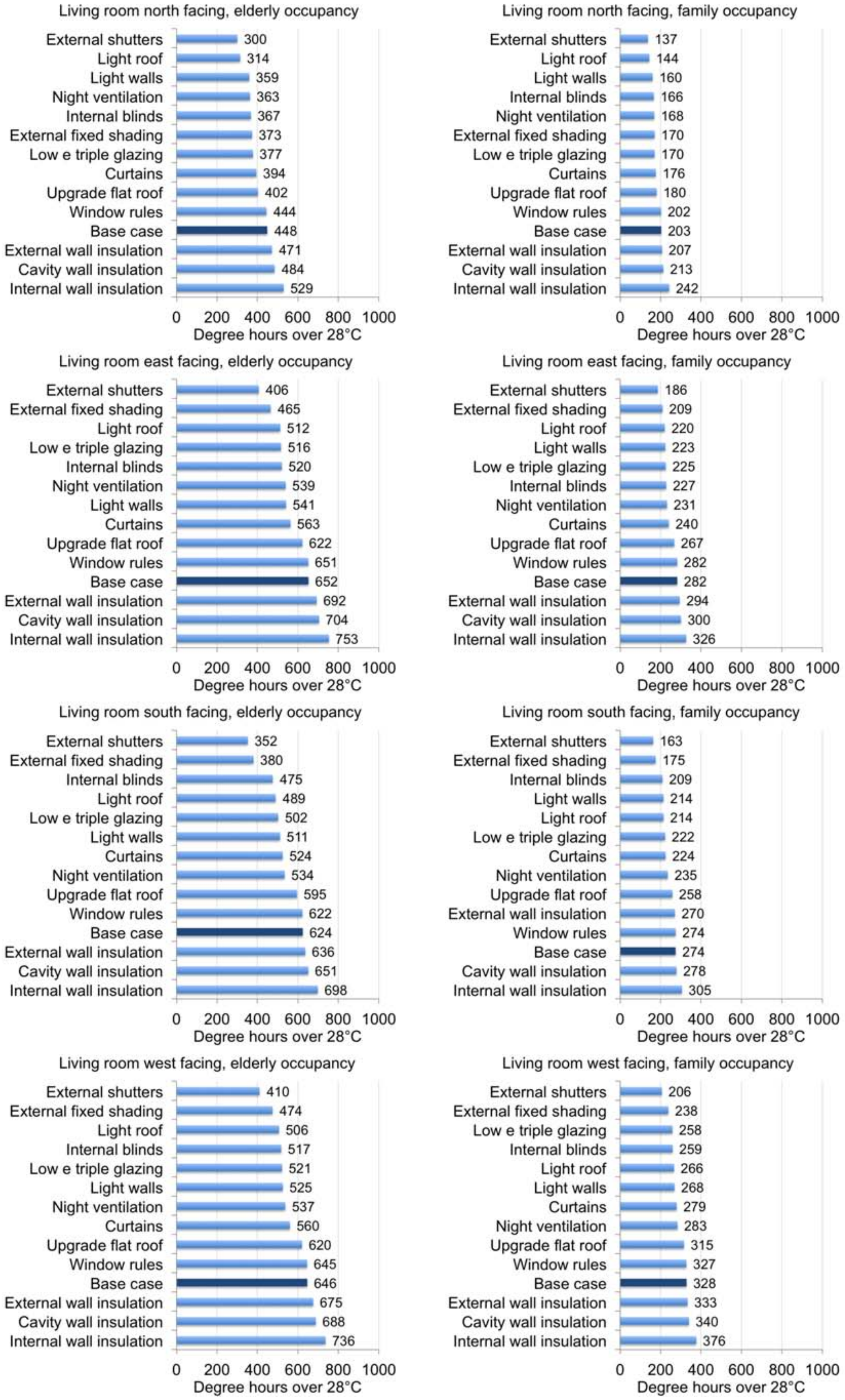

Figure 7.1 – Top floor flat living room overheating - single interventions

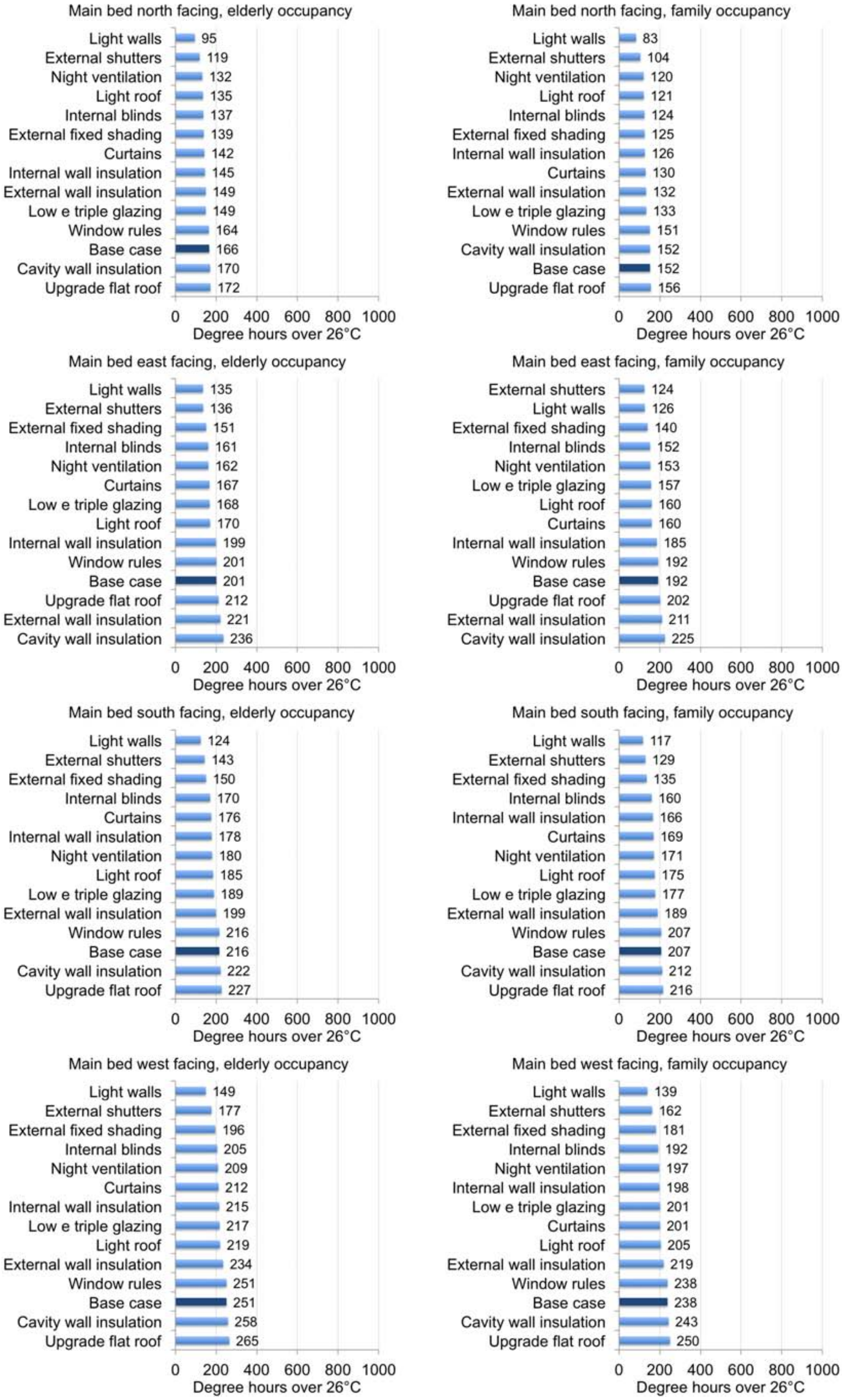

Figure 7.2 – Top floor flat main bedroom overheating - single interventions

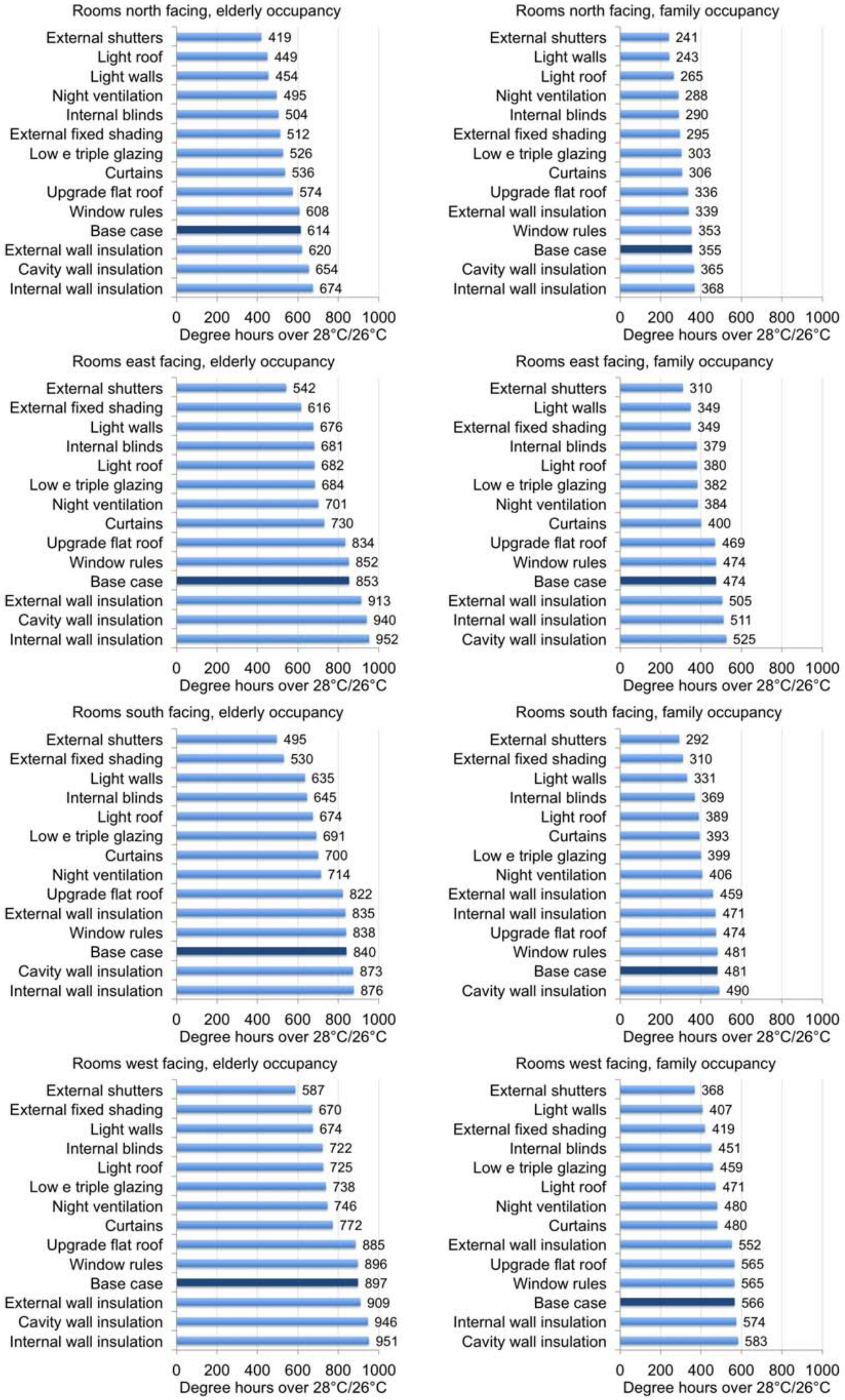

Figure 7.3 – Top floor flat total overheating - single interventions

the flat by convection. The window shading interventions were therefore effective for all dwelling orientations.

The benefits of keeping shutters, blinds and curtains closed during the daytime were also observed in the main bedroom, where reducing daytime solar heat gains resulted in lower internal temperatures at bedtime.

External shutters were the most effective single intervention when considering total overheating exposure (living room plus main bedroom for occupied periods) for both occupancy profiles and all orientations, reducing overheating by 32-41%.

7.2.1.2 Low e triple-glazing

The flats have a large glazed area as a proportion of external surface area. Low emissivity (low e) triple-glazing was an effective intervention, achieving comparable overheating reductions to curtains and blinds. Living room overheating was reduced by 16-21%, with the greatest reduction for elderly occupants in an east-facing living room, whereas family residents benefitted most in the west-facing living room.

7.2.1.3 External fixed shading

Overhangs fitted above south, east and west-facing windows were the second ranked intervention for orientations where the living room window was facing south, east or west, reducing overheating by up to 39% (south-facing window with elderly occupants). They were still a middle-ranked intervention for the living room with a north-facing window due to the effectiveness in reducing solar heat gains through south-facing windows at the front of the flat (bedroom 2, kitchen and bathroom). The main bedroom also benefitted from the fixed shading, which reduced heat gains and maintained lower temperatures.

7.2.1.4 Night ventilation

Night ventilation of the living room and kitchen removed heat gained during the daytime and as a result the internal temperature started from a lower base each morning. It also cooled the building fabric to provide a radiative cooling benefit from the internal surfaces. Overheating in the living room was reduced by up to 19% (north-facing windows with elderly occupancy) and in the main bedroom by up to 21% (also north-facing for both profiles).

7.2.1.5 Window rules

The window rules intervention reduced overheating for some of the dwelling types (see Chapter 8). However, it had little or no effect as a single intervention for the top floor flat. At nearly all times during the occupied periods the top floor flat room temperatures were greater than the outdoor dry bulb temperature, which indicates how severe the overheating problem can be for certain dwelling types (see Figure 8.16 in Chapter 8). It was, however, of some benefit when combined with other interventions (Section 7.3). In these cases the internal temperature was reduced by the other interventions to a point at which the window rules intervention could take effect.

7.2.1.6 Upgrade flat roof

Upgrading the flat roof attenuated the transmission of solar heat gains during the day and living room overheating was reduced by 4-11%. It was most effective when the front of the flat was south-facing (living room north-facing). However, the flat roof upgrade also resulted in heat gains in the main bedroom being more effectively retained at night time. This intervention increased bedroom overheating for all orientations and occupancy profiles by 3-6% and was the worst ranked intervention for south, west and north-facing main bedrooms. The overheating reduction for the living room combined with increased overheating for the main bedroom resulted in the effect on total overheating being small. The net effect varied from a 1 degree hour reduction (0.2%) for west-facing rooms with family occupancy to a 40 degree hour reduction (6.5%) for north-facing rooms with elderly occupancy.

7.2.1.7 Light roof

The outside black asphalt roof surface on the base case flats reached a peak temperature of 58.1 °C during the hottest heat wave day (10th August), whilst the inside surface temperature peaked at 36.6 °C. Figure 7.4 shows how the high performance solar reflective coating reduced the maximum outside surface temperature to 37.1 °C (21 °C reduction) and the inside surface temperature to 32.5 °C. The peak temperatures also occurred later in the afternoon, 3 hours after the base case peak temperatures.

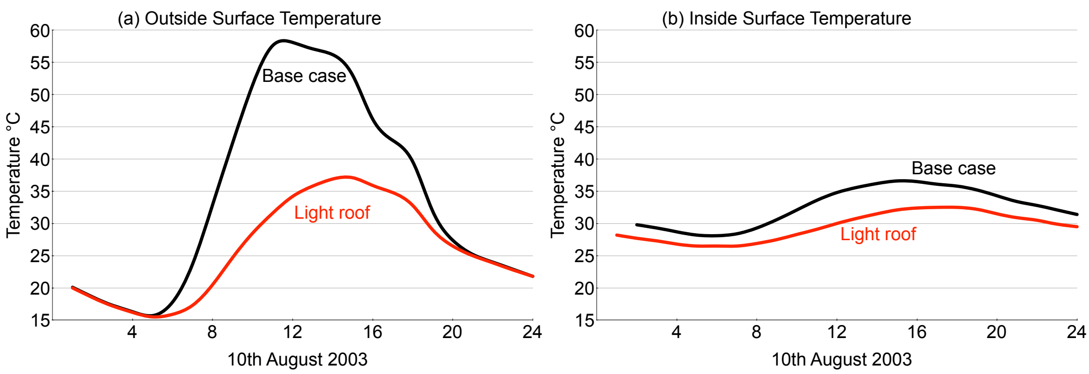

Figure 7.4 – Top floor flat roof surface temperatures

The light roof intervention was very effective for the living room, where a reduction in degree hours of almost 30% was recorded for the orientation with north-facing windows. Smaller reductions of between 13% and 20% were recorded for the main bedroom.

7.2.1.8 Light walls

There is a time lag between solar gains being absorbed by the outer bricks and the time they are transferred as heat gains to the rooms, with peak afternoon solar radiation continuing to heat the rooms during the evening and overnight (Figure 7.5).

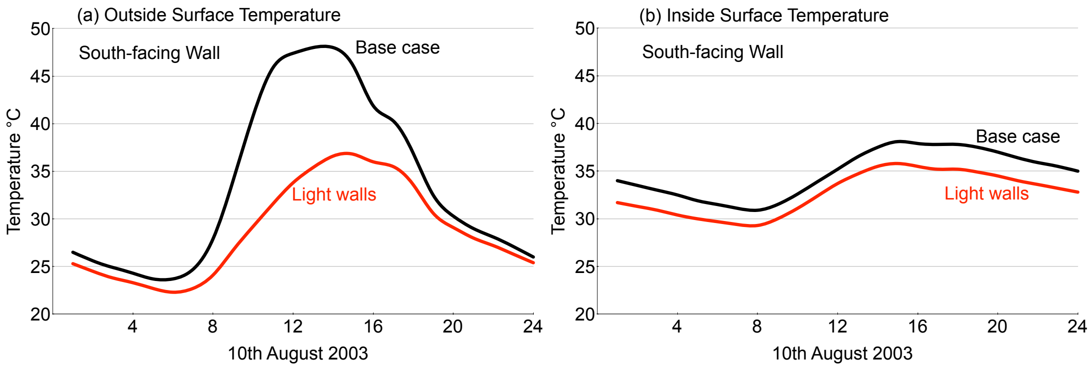

Figure 7.5 – Top floor flat living room wall temperatures

The light walls intervention was very effective for the main bedroom for all orientations, outperforming external shutters to be the most effective single intervention in all but one case (east-facing windows with family occupancy). The main bedroom has two external walls, one of which contains the glazing (see the floor plan in Figure 3.9). When the windows were east-facing the second wall was north-facing and this orientation showed the smallest overheating reduction (33-34%). For the other orientations it was the highest ranked intervention, reducing degree hours by up to 45%. The light walls intervention was also effective for living rooms, reducing overheating by 17-22% and it was the second or third highest ranked intervention for total overheating reduction in all cases, reducing degree hours by 21-32%.

7.2.1.9 Wall insulation

The effect of adding the three different types of wall insulation to the external walls varied depending on room type, orientation and occupancy profile. Considering the total overheating exposure (time spent in the living room and main bedroom combined), external wall insulation resulted in the lowest overheating.

For the living room, in all but one case (south-facing windows with family occupancy), the addition of any type of wall insulation increased overheating. External insulation resulted in the lowest overheating increase (between a 1% reduction and a 6% increase), whilst internal wall insulation produced the largest overheating increase (up to 19%).

The effect of wall insulation was different for main bedroom overheating. Figure 7.6 shows the effect that each type of wall insulation had on the inside wall surface temperature for the top floor flat main bedroom south-facing wall.

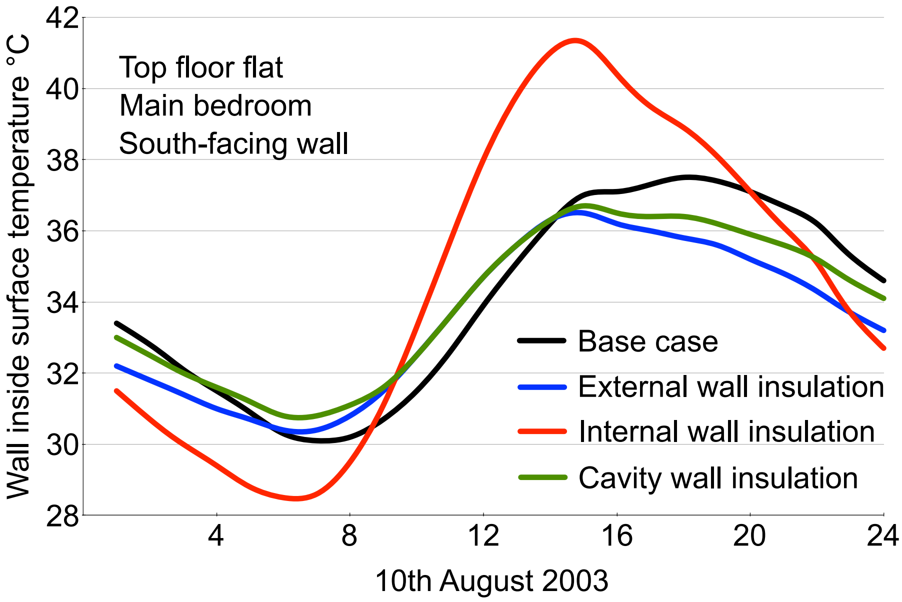

Figure 7.6 – Effect of wall insulation on inside surface temperatures

The main bedroom was only occupied at night and during this period internal wall insulation always resulted in less overheating, ranging from a 20% reduction in the south-facing main bedroom with family occupancy to a 1% reduction for the east-facing main bedroom with elderly occupancy. External wall insulation was the second best option for all cases, but varied from a 13% reduction for the north-facing main bedroom with family occupancy to a 10% increase for the east-facing main bedroom with elderly occupancy. The addition of cavity wall insulation lead to the greatest level of bedroom overheating, with a 17% increase for the east-facing main bedroom and from zero to a 3% increase for the other orientations.

The flats have a large glazed area and there was significant solar heat gain through the poorly insulated flat roof. The internal wall surfaces absorbed internal heat gains through the day as the room temperature rose and also received heat gains through the wall fabric from solar radiation incident on the outer brickwork.

When cavity wall insulation was installed the transfer of heat gains from exterior solar radiation was reduced during the daytime, but heat stored in the inner layer concrete blocks was not discharged as quickly at night. The same was true when external wall insulation was fitted, but to a lesser extent because some of the heat could discharge into the cavity. Internal wall insulation shielded the thermal mass of the inner wall concrete blocks from the rising room temperatures, but having little thermal inertia itself, warmed rapidly as the room temperature rose and also cooled more rapidly in the evening.

When considering the effect on total overheating (Figure 7.3), external always produced the lowest overheating of the three types of wall insulation. Internal insulation produced the highest overheating in all cases for elderly occupancy, but where the living room was not occupied during the daytime (family profile), cavity insulation resulted in the greatest overheating, except for the case where the rooms faced north, where internal insulation produced the greatest overheating.

7.2.2 Effect of occupancy on intervention ranking order

The elderly residents were assumed to occupy the dwellings 24 hours a day, whilst the family profile assumed that the dwellings were unoccupied during the daytime. The elderly residents were therefore occupying the dwellings during the hottest parts of the day and in the case of the top floor flat experienced up to 1.8 times the total overheating exposure of the family residents for the heat wave period.

Comparing results for the two occupancy profiles it can be seen that the ranking order for high and middle ranked interventions was largely unchanged, both for the living room and main bedroom. External shutters were the most effective intervention for the living room in all cases, but the charts (Figures 7.1 - 7.3) show that the relative effect of shutters for elderly occupants was greater.

The effect of adding different types of wall insulation was discussed in Section 7.2.1.9. Comparing occupancy profiles the ranking orders of the 3 types of insulation was the same for each room individually. However, internal wall insulation produced proportionally higher overheating for daytime occupancy of the living room and total overheating for elderly occupants was always greatest with the addition of internal wall insulation. Family occupancy was dominated by bedroom occupied periods, where cavity wall insulation produced the greatest overheating. Total overheating for family residents was greatest with the addition of cavity wall insulation for all cases except north-facing living room and main bedroom windows, where internal wall insulation resulted in slightly higher overheating.

7.2.3 Effect of interventions on heating energy use

To determine the annual space heating energy use the simulations were repeated for a whole year using the CIBSE London Heathrow test reference year (TRY) weather file (Section 2.8). The space heating energy use was simulated using the EnergyPlus ideal loads air system (Section 5.6) and the base case heating energy use figures for each dwelling were presented in Table 6.1 (Chapter 6). Table 7.2 shows the percentage change in heating energy use from the base case for each intervention, for the four orientations and two occupancy profiles for the top floor flat.

Shutters, blinds and curtains were assumed to be left open during the daytime in the heating seasons and therefore had no impact on heating energy use. Similarly, the two ventilation strategies (window rules and night ventilation) could be applied only when required during hot weather and would therefore not affect heating energy use.

	Changes in heating energy use from base case (%)							
	Elderly occupancy profile				Family occupancy profile			
	Front of block facing				Front of block facing			
Intervention	North	East	South	West	North	East	South	West
Internal blinds*	0	0	0	0	0	0	0	0
External shutters*	0	0	0	0	0	0	0	0
Curtains*	0	0	0	0	0	0	0	0
Low e triple glazing	-1.3	-2.6	-1.9	-2.3	-0.6	-2.4	-1.7	-1.9
External fixed shading	+6.9	+6.2	+5.2	+6.3	+7.3	+5.9	+4.9	+6.0
Night ventilation**	0	0	0	0	0	0	0	0
Window rules**	0	0	0	0	0	0	0	0
Upgrade flat roof	-15.3	-14.9	-15.1	-14.4	-14.3	-13.7	-13.6	-13.2
Light roof	+6.2	+6.1	+6.7	+6.1	+6.0	+5.6	+6.3	+5.7
Light walls	+8.4	+9.2	+8.0	+6.2	+8.8	+9.5	+8.3	+6.5
External wall insulation	-40.3	-37.4	-39.6	-38.9	-39.6	-36.3	-38.2	-37.9
Internal wall insulation	-40.0	-37.4	-39.6	-39.0	-39.1	-36.2	-38.0	-37.6
Cavity wall insulation	-33.3	-30.9	-32.7	-32.1	-32.1	-29.5	-31.2	-30.8

*Assumed not closed in the daytime during the heating seasons

**Assumed to be unused during the heating seasons

Table 7.2 – Effect of interventions on space heating energy use for top floor flats

In most cases the replacement of the existing double-glazing with low e triple-glazing produced a small reduction in space heating energy use (up to 2.7%). The lower U-value of the triple-glazed windows was offset by the loss of some beneficial solar gains during the heating season due to the low e coatings.

The overhangs above south, east and west-facing windows were assumed to be fixed[1], which increased annual space heating energy use. The lower solar altitude in winter did allow more direct solar heat gains through the windows than during the summer,

[1]Some of the shading devices above east and west-facing ground floor windows in other dwelling types were 2.0m awnings, which were assumed to be retracted during the heating season.

particularly for east and west-facing windows. However some direct solar radiation was still blocked, increasing heating energy use by up to 7.6% (Table 7.2).

Upgrading the flat roof included increasing the thickness and quality of the roof insulation, which reduced space heating energy use by 15-16%, whilst applying a solar control coating (light roof) reduced beneficial solar heat gains during the heating season, increasing heating energy use by up to 6.9%. Painting the walls with a solar reflective coating (light walls) also reduced beneficial solar gains during the heating season, increasing heating energy use by up to 10% when the living room and main bedroom had west-facing windows.

Adding wall insulation had the greatest effect on space heating energy use. Both internal and external wall insulation were specified to produce the same final wall U-value (0.35 W/m^2 K) and resulted in almost identical reductions in space heating energy use of between 39% and 42%. The cavity wall insulation produced a final wall U-value of 0.57 W/m^2 K and reduced space heating energy use by 30-34%.

7.3 Combined interventions

The effect on overheating reduction and space heating energy use of combining the single interventions was assessed systematically. The parameter tree structure described in Section 5.2.3 was used to control the EnergyPlus simulations through the jEPlus control interface.

A batch simulation for one orientation and occupancy profile for the top floor flat model produced 2,048 separate sets of simulation results, each describing single or combined interventions. Presentation of the results using the bar chart method (employed for the single intervention results) would not have been possible due to the large number of results, therefore a different presentation method has been adopted. Scatter plots are used, which enable the incorporation of both space heating energy use and intervention cost.

Figure 7.7 shows a scatter plot for the top floor flat with elderly occupancy and east-facing living room and main bedroom windows. The base case dwelling represents zero cost with a total of 853 degree hours total overheating predicted (living room plus main bedroom for occupied periods). The chart shows how overheating can be reduced as the cost of interventions increases (zone B). The size of the markers denotes the magnitude of the increase or decrease in heating energy use. Figure 7.7 shows how the greatest reductions in overheating are at the expense of space heating energy use until the cost increases significantly. The chart can also be used to identify those single and combined interventions that lead to increased overheating (zone A, above the dotted line).

Filters were applied to the results to determine the best performing intervention combinations considering four cost bands: Free, low cost (up to £5k), medium cost (£5k - £10k) and high cost (over £10k). The first filter identified interventions that produced the lowest overheating degree hours at the lowest cost within the band, regardless of the space heating energy use (unless more than one combination met the criteria, in which case the combination with the lowest heating energy use was chosen). The second filter selected interventions that produced the lowest space heating energy use combined with low overheating (i.e. if more than one set of interventions had the same lowest heating energy use, the one with the lowest overheating was selected). A graphical example of the two sets of filtered results is shown in Figure 7.8. Table 7.4 contains the filtered results for all four orientations and both occupancy profiles. The key to the short codes used for the interventions is contained in Table 7.3.

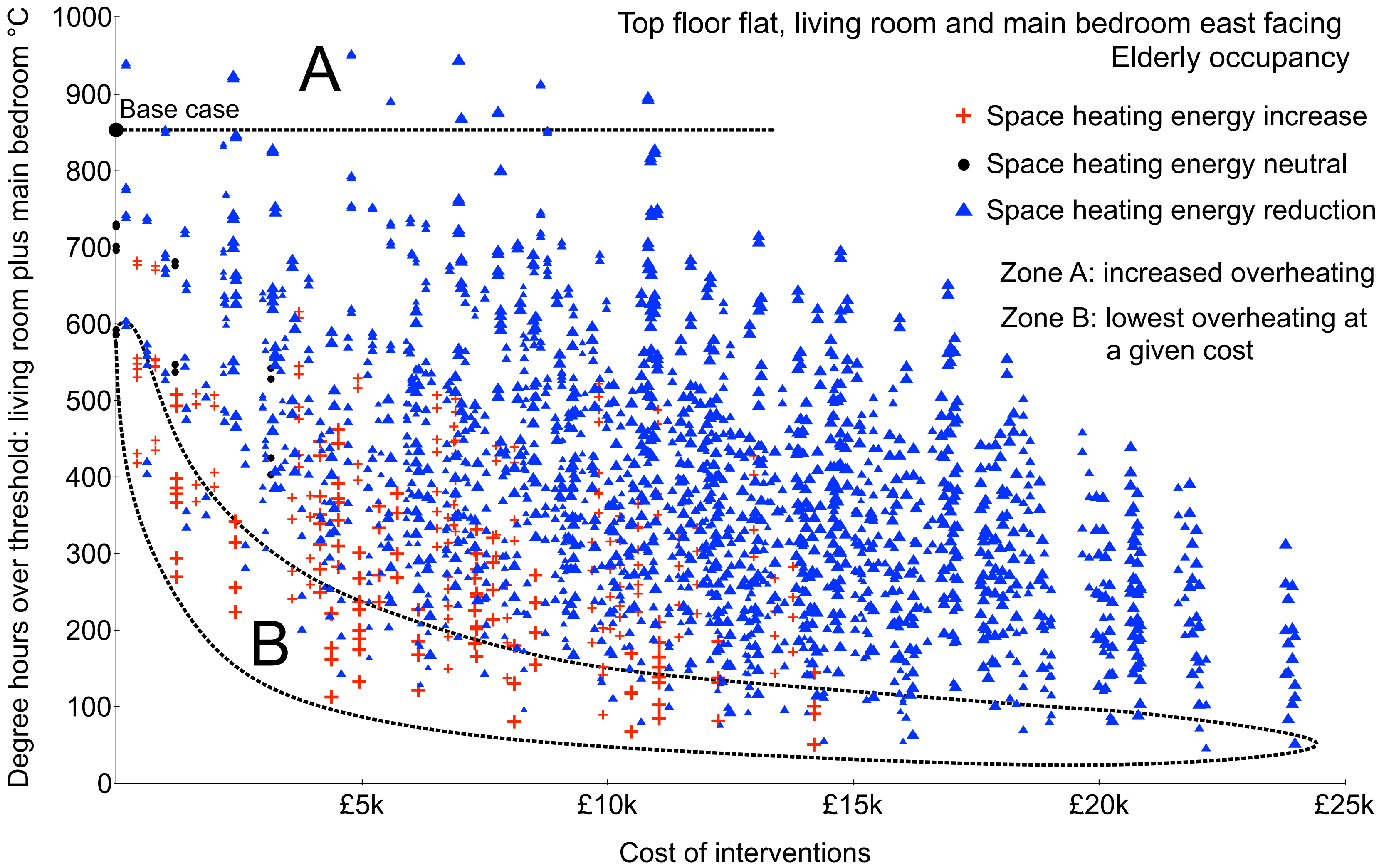

Figure 7.7 – Top floor flat overheating, energy use and cost

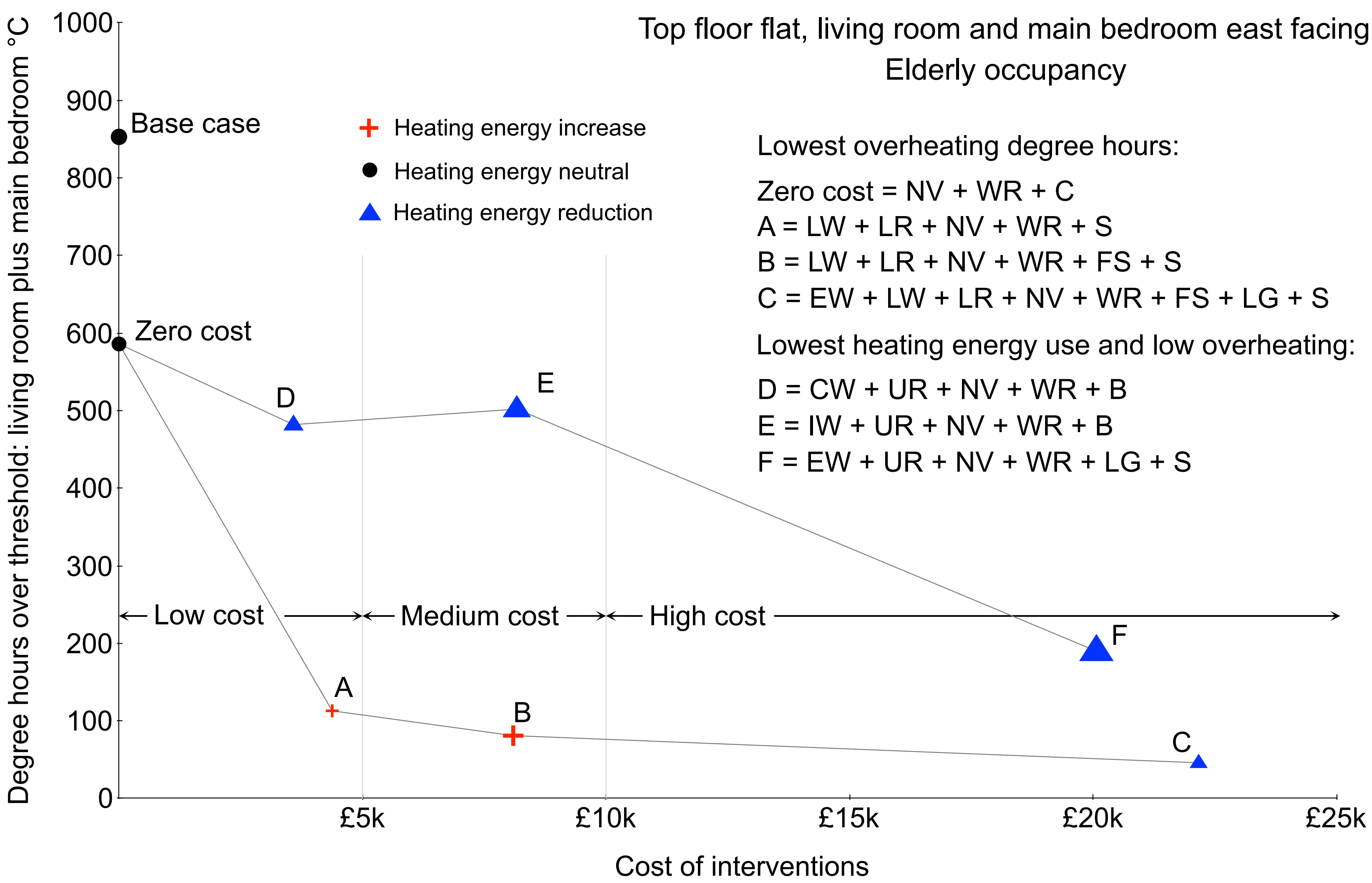

Figure 7.8 – Top floor flat filtered results from Figure 7.7, see Table 7.3 for intervention codes

Code	Intervention
B	Internal blinds
S	External shutters
C	Curtains
LG	Low e triple glazing
FS	External fixed shading
NV	Night ventilation
WR	Window rules
UR	Upgrade flat roof
L	Loft insulation
LR	Light roof
LW	Light walls
EW	External wall insulation
IW	Internal wall insulation
CW	Cavity wall insulation

Table 7.3 – Key to intervention codes in Figure 7.8 and Table 7.4

The major limitation of the scatter plot approach is the lack of labelling, which would be impossible for all points on the scatter plots. This makes identification of intervention combinations difficult. In particular, there may be a more suitable set of interventions from a practical viewpoint that are close in performance to the best performing ones at a given cost. This problem has been addressed in a prototype web toolkit, which is discussed in Section 7.4 and Appendix B. The toolkit can be accessed online (Porritt, 2011) and a CD-ROM containing the toolkit has been included in printed copies of this thesis to enable easy interrogation of the research output. It is suggested that the toolkit is used to view the results discussed in the following sections.

7.3.1 Greatest overheating reduction

The results in section (a) of Table 7.4 show the best combined interventions for reducing overheating during the heat wave period for different retrofit budgets.

In each case the three zero cost behavioural interventions: window rules, night ventilation and keeping the curtains closed during the daytime, reduced total overheating

		Elderly occupancy profile					Family occupancy profile				
Orientation	Cost	Base DH	DH (%)	H (%)	Interventions (see key in Table 7.3)	£k	Base DH	DH (%)	H (%)	Interventions	£k
(a) Maximum overheating reduction at the lowest cost in each band											
Front North	Zero	**840**	583 (-31)	0	NV+WR+C	0	**481**	326 (-32)	0	NV+WR+C	0
	Low		74 (-91)	+25	LW+LR+NV+WR+FS+B	4.4		43 (-91)	-15	CW+LW+LR+NV+WR+FS+B	4.6
	Med		47 (-94)	-16	CW+LW+LR+NV+WR+FS+S	6.6		26 (-95)	-15	CW+LW+LR+NV+WR+FS+S	6.6
	High		22 (-97)	-29	EW+LW+LR+NV+WR+FS+LG+S	20.5		10 (-98)	-27	EW+LW+LR+NV+WR+FS+LG+S	20.5
Front East	Zero	**897**	635 (-29)	0	NV+WR+C	0	**566**	404 (-29)	0	NV+WR+C	0
	Low		141 (-84)	+16	LW+LR+NV+WR+S	4.4		101 (-82)	+16	LW+LR+NV+WR+S	4.4
	Med		103 (-89)	+24	LW+LR+NV+WR+FS+S	8.1		75 (-87)	+23	LW+LR+NV+WR+FS+S	8.1
	High		58 (-94)	-28	EW+LW+LR+NV+WR+FS+LG+S	22.2		36 (-94)	-27	EW+LW+LR+NV+WR+FS+LG+S	22.2
Front South	Zero	**614**	420 (-32)	0	NV+WR+C	0	**355**	242 (-32)	0	NV+WR+C	0
	Low		57 (-91)	+16	LW+LR+NV+WR+S	4.4		35 (-90)	-22	CW+LW+LR+NV+WR+S	4.6
	Med		47 (-92)	+22	LW+LR+NV+WR+FS+S	6.1		28 (-92)	-17	CW+LW+LR+NV+WR+FS+S	6.3
	High		24 (-96)	-30	EW+LW+LR+NV+WR+FS+LG+S	20.2		11 (-97)	-29	EW+LW+LR+NV+WR+FS+LG+S	20.2
Front West	Zero	**853**	586 (-31)	0	NV+WR+C	0	**474**	317 (-33)	0	NV+WR+C	0
	Low		113 (-87)	+13	LW+LR+NV+WR+S	4.4		68 (-86)	+13	LW+LR+NV+WR+S	4.4
	Med		81 (-91)	+21	LW+LR+NV+WR+FS+S	8.1		50 (-89)	+20	LW+LR+NV+WR+FS+S	8.1
	High		46 (-95)	-31	EW+LW+LR+NV+WR+FS+LG+S	22.2		24 (-95)	-29	EW+LW+LR+NV+WR+FS+LG+S	22.2
(b) Optimum for space heating energy reduction with low overheating - zero cost always the same as (a)											
Front North	Low	**840**	422 (-50)	-49	CW+UR+NV+WR+B	3.6	**481**	228 (-53)	-48	CW+UR+NV+WR+B	3.6
	Med		440 (-48)	-56	IW+UR+NV+WR+B	8.2		230 (-52)	-55	IW+UR+NV+WR+B	8.2
	High		147 (-83)	-61	EW+UR+NV+WR+LG+S	20.1		78 (-84)	-58	EW+UR+NV+WR+LG+S	20.1
Front East	Low	**897**	501 (-44)	-47	CW+UR+NV+WR+B	3.6	**566**	317 (-44)	-45	CW+UR+NV+WR+B	3.6
	Med		515 (-43)	-54	IW+UR+NV+WR+B	8.2		321 (-43)	-52	IW+UR+NV+WR+B	8.2
	High		212 (-76)	-59	EW+UR+NV+WR+LG+S	20.1		130 (-77)	-56	EW+UR+NV+WR+LG+S	20.1
Front South	Low	**614**	291 (-53)	-49	CW+UR+NV+WR+B	3.6	**355**	162 (-54)	-46	CW+UR+NV+WR+B	3.6
	Med		319 (-48)	-56	IW+UR+NV+WR+B	8.2		176 (-53)	-53	IW+UR+NV+WR+B	8.2
	High		113 (-82)	-60	EW+UR+NV+WR+LG+S	20.1		60 (-83)	-57	EW+UR+NV+WR+LG+S	20.1
Front West	Low	**853**	482 (-43)	-47	CW+UR+NV+WR+B	3.6	**474**	264 (-44)	-45	CW+UR+NV+WR+B	3.6
	Med		502 (-41)	-55	IW+UR+NV+WR+B	8.2		264 (-44)	-52	IW+UR+NV+WR+B	8.2
	High		190 (-78)	-59	EW+UR+NV+WR+LG+S	20.1		104 (-78)	-57	EW+UR+NV+WR+LG+S	20.1

DH (%) = Total overheating degree hours % change from base case; H (%) = Heating energy use % change from base case

Table 7.4 – Top floor flat combined interventions

by around 30%. However, the base case overheating for the top floor flat was so high that the number of degree hours over the threshold temperatures was still between 420 and 635 for elderly occupants and 242-404 in the case of family occupants.

It was possible to reduce overheating by 82-91% using a low cost (up to £5k) package of interventions, reducing overheating for elderly occupants to between 57 and 141 degree hours and 35-101 degree hours for family occupants. In all but two cases the greatest overheating reduction was at the expense of increased heating energy use (up to 25% higher). In the case of family occupancy with the front of the block either north or south-facing the inclusion of cavity wall insulation in the low cost combined interventions resulted in a net reduction of 15-22% in heating energy use.

The medium cost packages reduced overheating further (87-95%), but there were still cases where the optimum interventions for overheating reduction increased heating energy use due to solar control interventions with no insulation upgrades.

The same package of high cost interventions was found to be the most effective in all cases: external wall insulation, light walls and roof, night ventilation, window rules, fixed external shading, low e triple-glazing and external shutters. The cost ranged from £20.2k to £22.2k due to the cost of external fixed shading varying between orientations. It was not possible to eliminate overheating, but the greatest reductions were achieved for the front north-facing orientation (living room and main bedroom south-facing), where elderly occupancy overheating was reduced by 97% from 840 to 22 degree hours and family occupancy overheating by 98% from 326 to 10 degree hours (Table 7.4(a)). Heating energy use was reduced by the addition of external wall insulation and low e triple-glazing, but this reduction was offset by the fixed solar control interventions, producing a net reduction of 27-31% in annual heating energy use.

7.3.2 Greatest heating energy use reduction with low overheating

Combined interventions were also selected for maximum heating energy use reduction at the lowest cost within each cost band (Table 7.4(b)). Where more than one combination produced the same maximum heating energy use reduction, the one that produced the greatest overheating reduction was selected.

In each case the fixed solar control interventions (light walls, light roof and external fixed shading) were not included, because they would have increased energy use during the heating season. Solar control was achieved by the use of internal blinds or external shutters, depending on budget, which can be left open during the daytime in the heating seasons to provide beneficial solar heat gains. Similarly, the ventilation control strategies could be included, because they could be omitted during the heating seasons.

For the low cost budget (up to £5k), cavity wall insulation and upgrading the flat roof reduced heating energy use by up to 49%. The ventilation interventions and closing blinds during the daytime reduced overheating, but it remained very high compared to the low cost interventions for maximum overheating reduction (Table 7.4(a)).

The medium cost budget (£5k - £10k) allowed the installation of internal wall insulation, reducing heating energy use further (up to 56%). However, this was at the expense of slightly increased overheating (except for the front west-facing with family occupancy, where overheating reduction remained the same at 44%).

The high cost budget (over £10k) allowed the installation of external wall insulation, which was shown to perform better than internal or cavity wall insulation for overheating reduction (Section 7.2.1.9). External wall insulation produced similar heating energy reductions to internal wall insulation and the addition of low e triple-glazing reduced energy use further. The total heating energy use reduction from fitting external wall insulation, low e triple-glazing and upgrading the flat roof was between 56% and 61%. The high cost package of interventions also included the two ventilation strategies and external shutters, reducing overheating to between 113 and 212 degree hours for elderly occupants and 60-130 degree hours for family occupants.

7.4 Using the retrofit toolkit to select alternative interventions

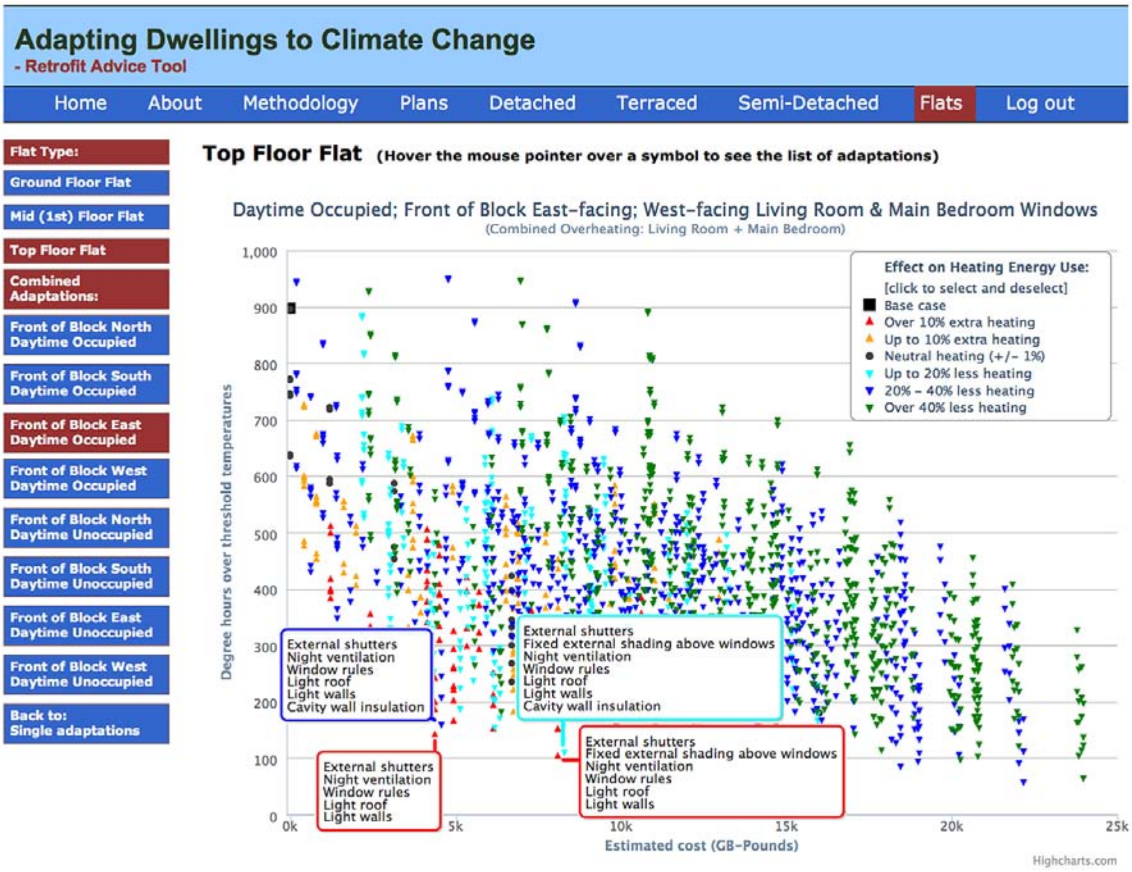

Figure 7.9 – Toolkit screenshot: effect of adding cavity wall insulation to low and medium cost interventions

Identifying which interventions each point in the scatter plots represents was time consuming, making comparisons between dwelling types, orientations and occupancy profiles difficult. Also, labelling each point in printed versions of the thesis would be impossible. A retrofit toolkit was developed to demonstrate the use of this research, which uses a set of HTML pages to display bar charts for single interventions and interactive scatter plots for the combined interventions. The toolkit is described in detail with some example screenshots in Appendix B, which also contains a physical copy on CD-ROM for printed versions of the thesis.

Using the toolkit to examine the combined intervention results discussed in Sections 7.3.1 and 7.3.2, it can be seen that in many cases there are alternative combinations which may be considered.

In Section 7.3.1, all but one of the low cost intervention packages resulted in greater heating energy use. Using the toolkit (Figure 7.9) shows that adding cavity wall insulation to the intervention packages reduces heating energy use by 16-25%, for a small penalty (0.5-4%) in overheating reduction, at an estimated additional cost of £200 (subsidised cost to householders).

The addition of cavity wall insulation to those medium cost combined interventions that produced increased heating energy use had a small impact on overheating reduction, but reduced heating energy use by 14-18%. For the worst case orientation (front east-facing, rooms west-facing) the addition of cavity wall insulation increased overheating compared to the best medium cost intervention package by 8 degree hours (less than 1%) and for family occupants by 1 degree hour (0.2%), whilst reducing heating energy use from the base case by 15% and 14% respectively (Figure 7.9).

Depending on the priority, high cost combined interventions were able to either reduce overheating by up to 98%, whilst reducing heating energy use by up to 31%, or reduce heating energy use by up to 61% with a maximum overheating reduction of 61%. Again, using the toolkit, it is possible to find alternative combinations that performed almost as well for overheating reduction but significantly better for heating energy use. For example, where the front is north-facing (south-facing living room and main bedroom) with elderly occupancy, if the upgraded roof intervention is added to the high cost combined interventions for greatest overheating reduction (Figure 7.10), at an estimated additional cost of £1.8k (per flat shared cost), the net effect on heating energy use changes to a 52% reduction, whilst only increasing total overheating degree hours from 22 to 24.

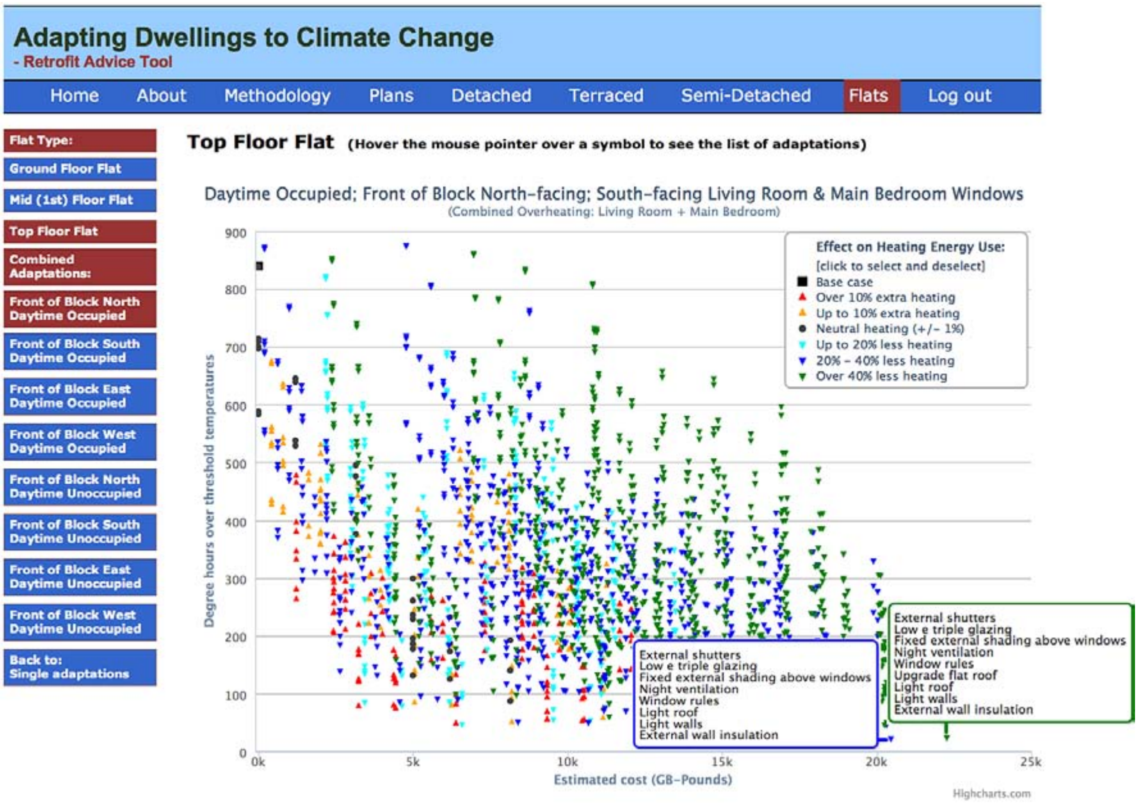

Figure 7.10 – Toolkit screenshot: effect of adding roof upgrade to high cost interventions

7.5 Summary

This chapter presented the simulation results for the top floor flat, starting with the effect of single interventions on overheating and space heating energy use. External shutters were shown to be the best performing intervention for living room and total overheating reduction for all orientations and both occupancy profiles, whilst light walls was generally the highest ranked intervention for the main bedroom. Wall insulation was found to increase overheating in most cases, with internal wall insulation performing worst for the living room and cavity wall insulation worst for the main bedroom.

Combined interventions were able to reduce overheating by up to 97%, with around a 30% reduction in heating energy use. Alternative interventions could reduce heating energy use by up to 61%, but with a compromise in overheating reduction to around 80%. The retrofit toolkit was introduced and it was demonstrated how the toolkit could be used to explore the simulation results and find alternative intervention combinations.

Chapter 8

Results 3: Adaptations for all dwelling types

8.1 Foreword

Chapter 6 compared the base case performance of all the dwellings, whilst Chapter 7 presented the simulation results for one type in detail, the top floor flat, which was found to be the worst performing dwelling for overheating.

This chapter presents the results for the remaining dwelling types, demonstrating how built form, occupancy and orientation can affect the single intervention ranking order for overheating reduction. Combined intervention results are also presented for each dwelling and the effect on space heating energy use and the cost of interventions is discussed. Chapter 9 will then discuss the results presented in this and the previous two chapters to compare the effect of interventions across dwelling types

8.2 Single interventions for overheating reduction

The base case simulations (Chapter 6) highlighted the different overheating exposure experienced by each dwelling type and the range of overheating for different orientations and occupancy profiles within each dwelling type. The most effective intervention for reducing total overheating for the top floor flat (Chapter 7) was found to be external shutters, for all orientations and both occupancy profiles. The shutters intervention was also found to be particularly effective across the dwelling types, although it was not always the best performing intervention. In this section the single intervention ranking charts for living rooms, main bedrooms and total overheating (living room plus main bedroom) are presented for each dwelling type, with the exception of the top floor flat single intervention results, which were presented in Chapter 7.

8.2.1 Terraced houses

The terraced house living rooms are at the front and the main bedrooms at the rear (see the floor plans in Figure 3.3). Therefore total overheating results combined rooms facing in opposite directions. For north/south orientations windows on one side were exposed to large amounts of solar radiation and windows on the other side received very little. The end-terraced house also has second external walls for both the living room and main bedroom. Living room overheating exposure was found to be significantly higher for elderly occupants than family occupants, being around three times higher in the end-terraced house and three to five times higher in the mid-terraced house.

8.2.1.1 End-terraced house

Figures 8.1 - 8.3 present the overheating ranking charts for the living room, main bedroom and total overheating for the end-terraced house.

The solid brick external walls are effective conductors of solar heat gains and the external wall area of the end-terraced house is significantly greater than for the mid-terraced house. The end-terraced house roof space has the same tiled area as the mid-terraced house, but in addition has an external solid brick end wall, therefore the light walls intervention also reduced solar heat gains to the loft space. The light walls intervention produced the greatest total overheating reduction for all orientations and both occupancy profiles, reducing overheating by between 48% (front west, elderly occupancy) and 65% (front north, family occupancy - in which case the end wall was east-facing and the rear of the house south-facing).

External wall insulation provided another means of shielding the external brickwork from direct solar radiation and was also very effective for the end-terraced house. It was ranked in the top four in all cases except for the west-facing living room with elderly occupancy. In this case the end wall (living room second unglazed wall) was facing north and interventions that reduced solar heat gains through the glazing were more effective. External shutters were the most effective intervention for this case, reducing overheating by 53%. As discussed in Chapter 7, external shutters were more effective than internal blinds, which in turn were more effective than curtains.

Internal wall insulation was found to be consistently worse than external wall insulation for overheating reduction and, in the case of the west-facing living room and east-facing main bedroom, resulted in total overheating degree hours increasing by 18%. In this case the second (unglazed) walls in the living room and main bedroom were north-facing. For the other three orientations, where the second walls were south, east or west-facing, the internal wall insulation prevented some of the solar heat gains incident on the end wall from transferring to the rooms and reduced total overheating by up to 40% (north-facing living room and south facing main bedroom with family occupancy).

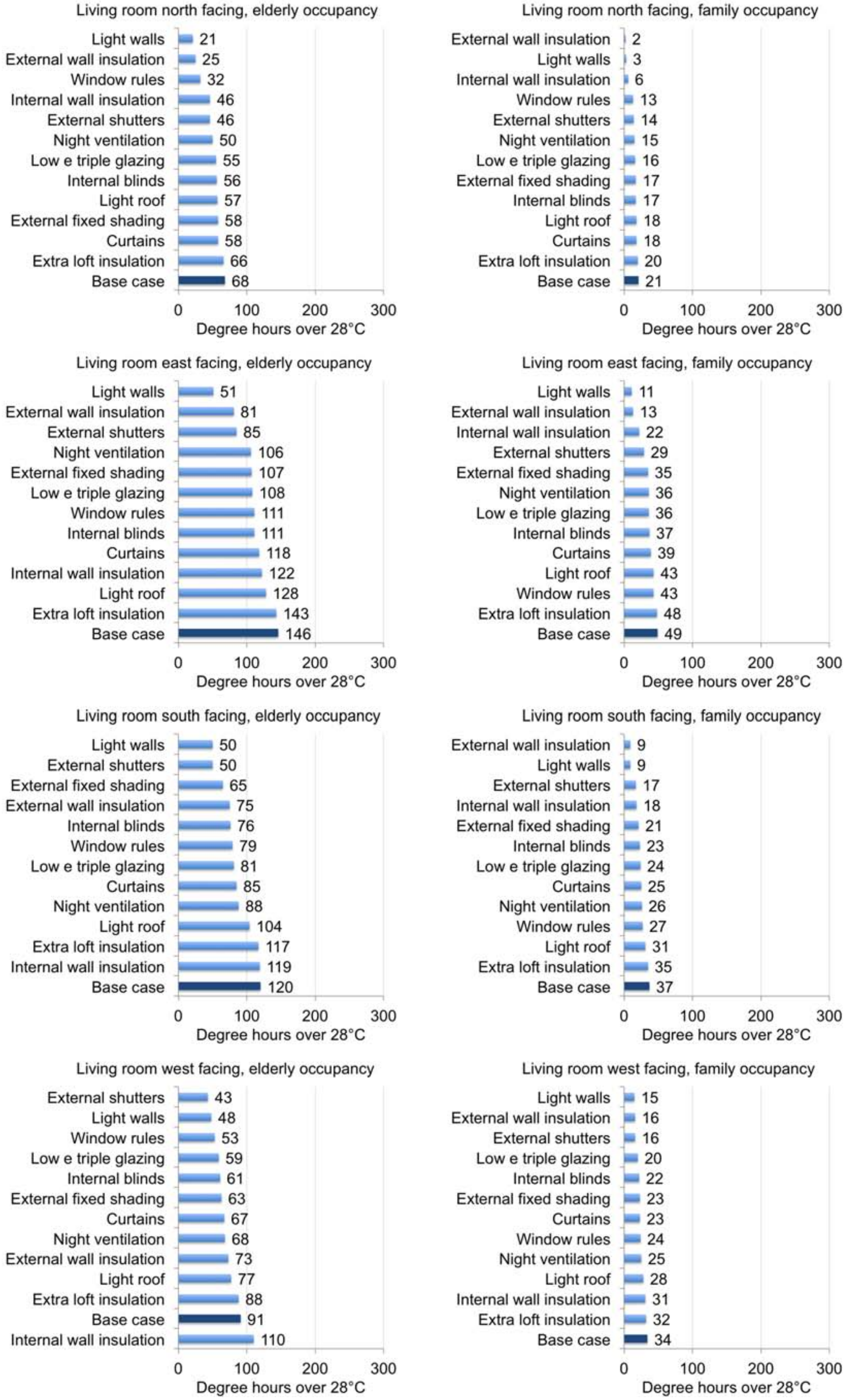

Figure 8.1 – End-terraced house living room overheating - single interventions

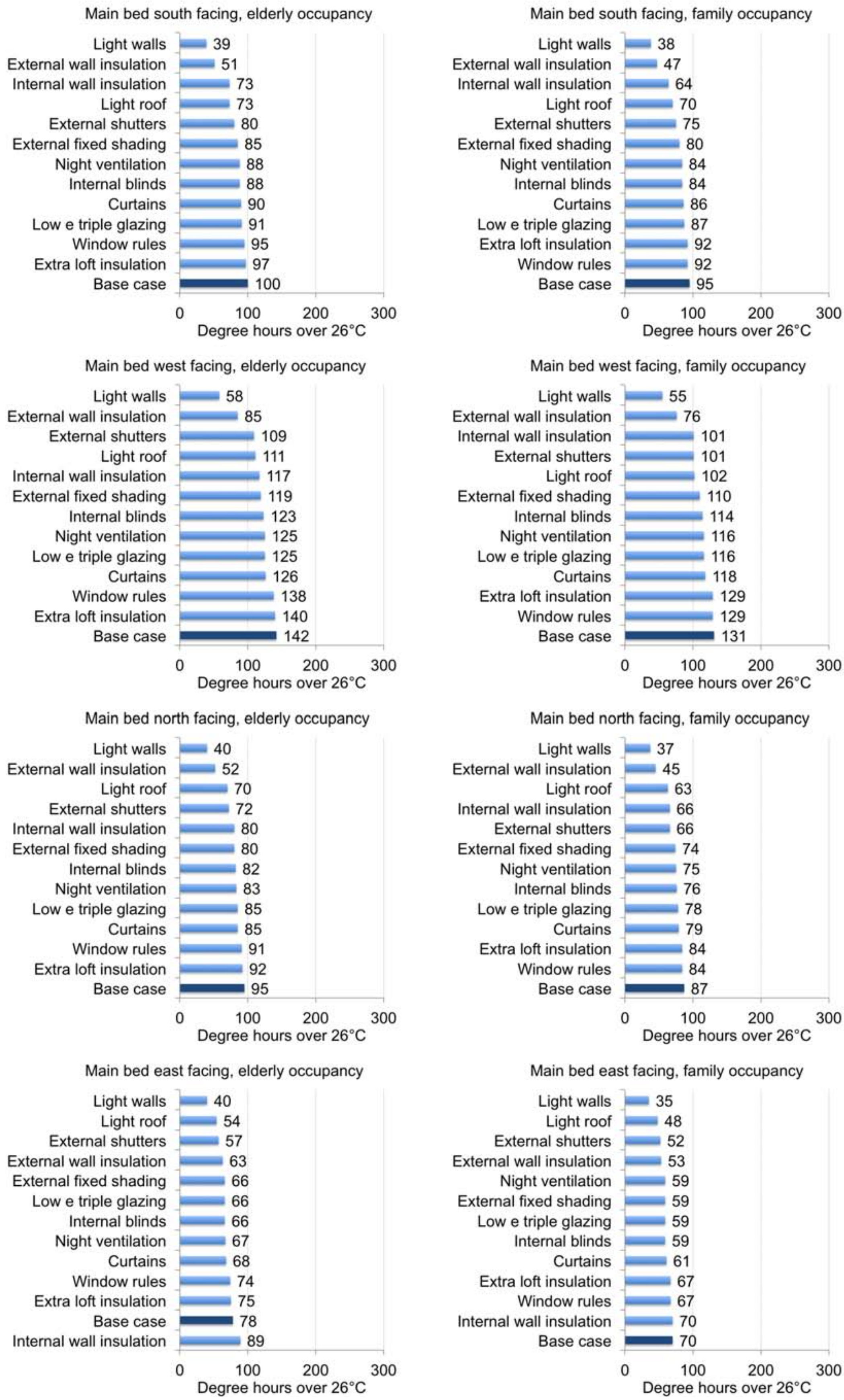

Figure 8.2 – End-terraced house main bedroom overheating - single interventions

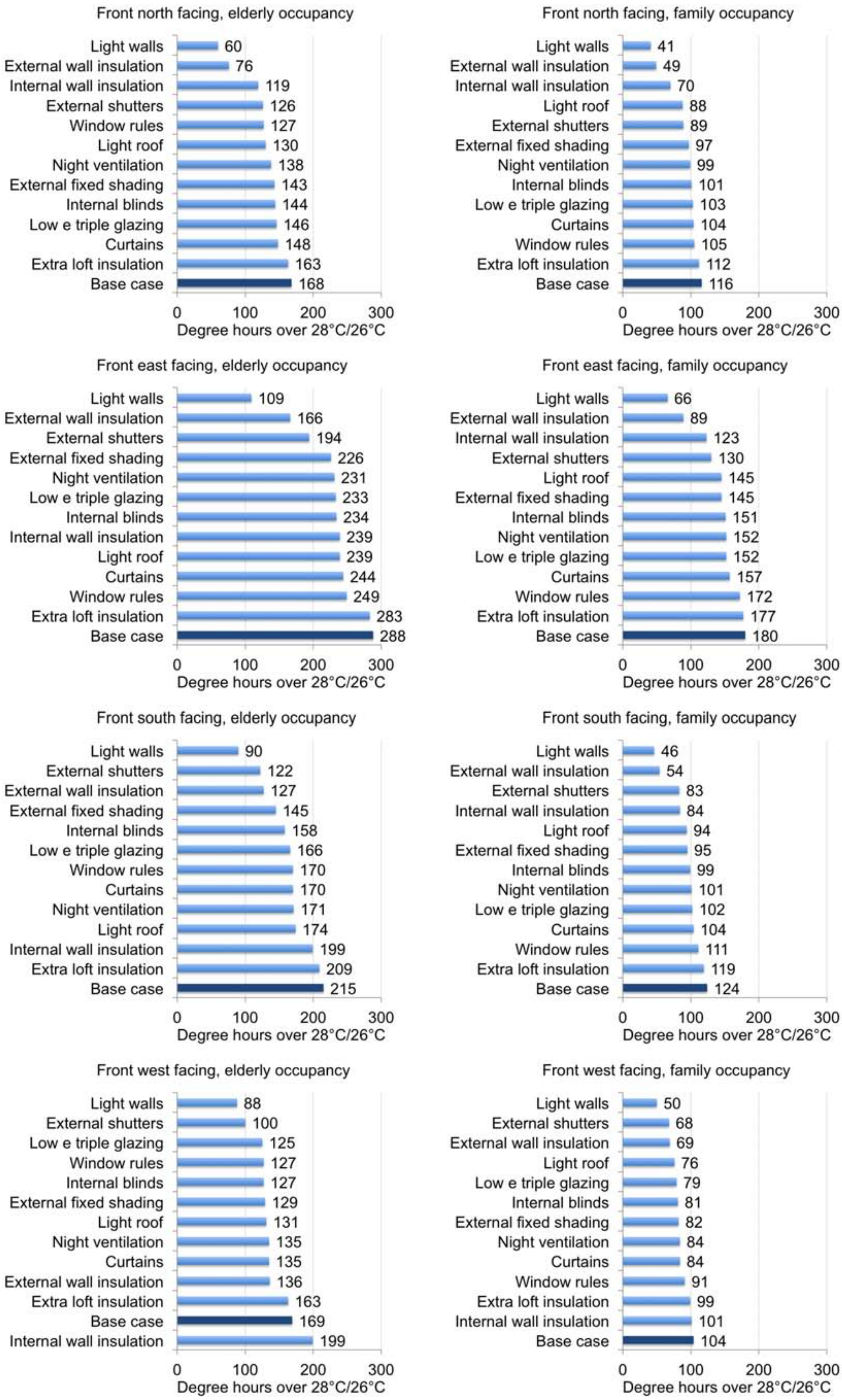

Figure 8.3 – End-terraced house total overheating - single interventions

Fixed shading above the windows was most effective for south-facing windows, where the high solar altitude resulted in most of the direct solar radiation being shielded from the glazing. Total overheating was reduced by 46% for the south-facing living room with elderly occupancy.

Unlike the top floor flat, room temperatures in the end-terraced house were below the outdoor dry bulb temperature during the afternoon peak periods. The window rules intervention was therefore very effective for rooms occupied during the daytime and reduced overheating by 53% for elderly occupants in the north-facing living room. The night ventilation strategy cooled the building fabric overnight and reduced total overheating by 15-21%, being most effective for the living room, reducing overheating by 27-30%. The bedroom windows were already assumed to open at night during hot weather, but the benefit of opening ground floor windows at night was seen in the main bedroom, where overheating was reduced by 12-16%.

Total overheating was reduced by up to 26% by the replacement of the windows with low e triple-glazing. It was most effective in the living room with west-facing windows, where it reduced overheating by 41% for family occupants. The impact on bedroom overheating was much lower, with reductions of 8-16%.

The light roof intervention was effective for the main bedroom, reducing overheating by up to 31% when the bedroom was west-facing. Increasing the level of loft insulation prevented some of the solar heat gains from the loft space transferring to the living areas, but only reduced total overheating by 2-5%.

8.2.1.2 Mid-terraced house

Figures 8.4 - 8.6 contain the overheating ranking charts for the mid-terraced house.

External wall insulation was, in common with the end-terraced house, more effective at reducing overheating than internal wall insulation. For the mid-terraced house there were no cases where the total overheating was increased by the addition of internal wall insulation, although there was a slight increase in overheating for the north and west-facing main bedroom. External wall insulation was not ranked as high for the mid-terraced house due to the smaller external wall area compared to the end-terraced house, resulting in the glazed area being a higher proportion of the external facade area.

The proportionally higher glazed area moved glazing solar protection interventions up the rankings. External shutters were very effective at reducing total overheating and were the best performing intervention when the front of the dwelling faced west and south with elderly occupancy. Overheating for elderly residents in the south facing living room was reduced by 67% to 36 degree hours by adding shutters. Low e triple-glazing performed slightly better in the mid-terraced house, reducing overheating in the west-facing living room with family occupancy by 47% and total overheating by 28%.

External fixed shading was again very effective for south-facing rooms, reducing living room overheating by 54% (elderly occupancy) and 58% (family occupancy). Fixed shading over the east and west-facing windows could not block all the direct solar radiation, but still reduced overheating by 31-44%.

Even though the external wall area was less than the end-terraced house, the light walls intervention was still very effective and for family occupancy was the highest ranked intervention for total overheating for all four orientations. The light roof intervention was very effective for the mid-terraced house, reducing total overheating by up to 45%. For north or south orientations one of the roof surfaces was south-facing and the light roof intervention was the highest ranked intervention for the main bedroom in these cases. The mid-terraced roof space (unlike the end-terraced house) does not have any external wall area and coating the roof tiles reduced all direct solar heat gains to the loft space.

Figure 8.4 – Mid-terraced house living room overheating - single interventions

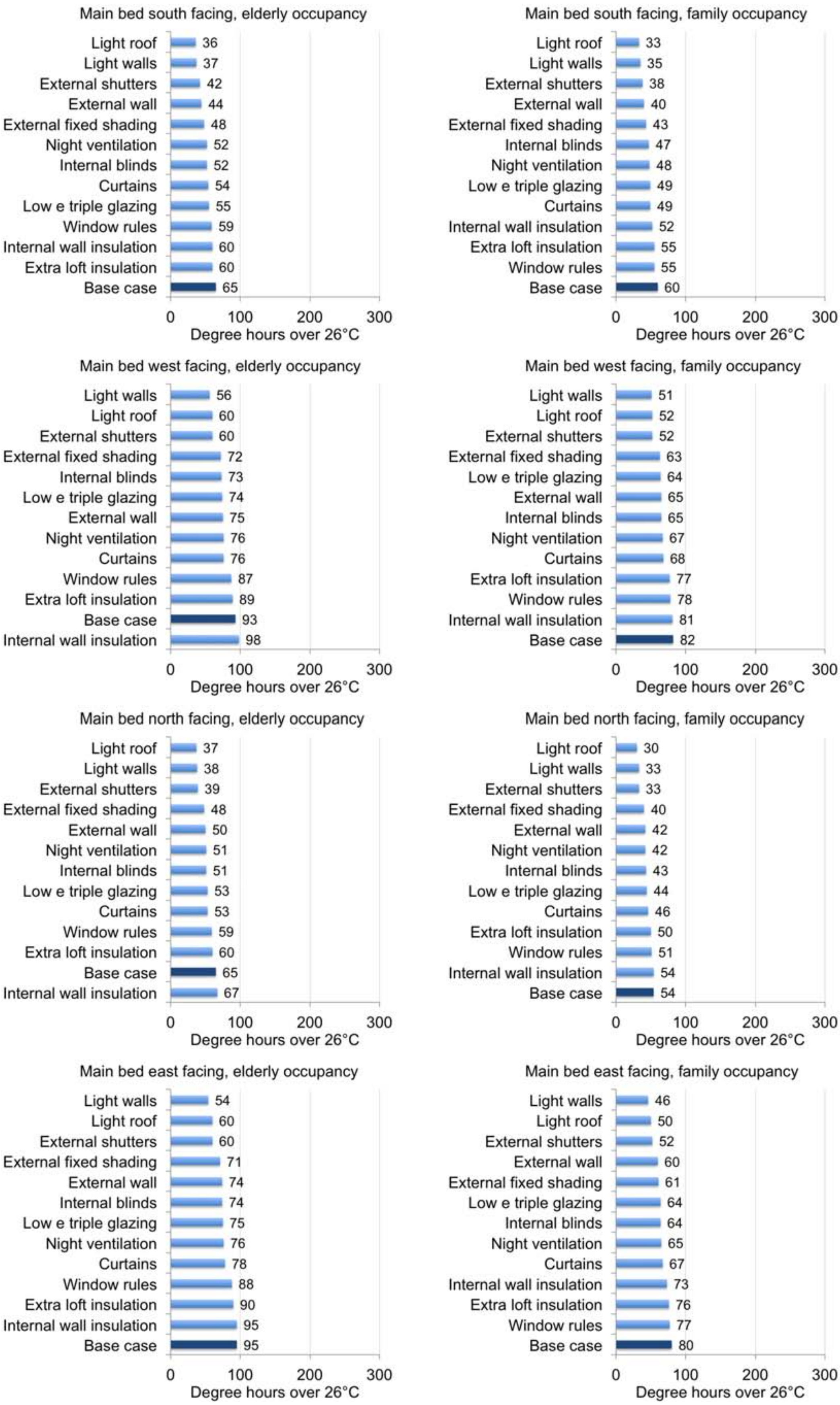

Figure 8.5 – Mid-terraced house main bedroom overheating - single interventions

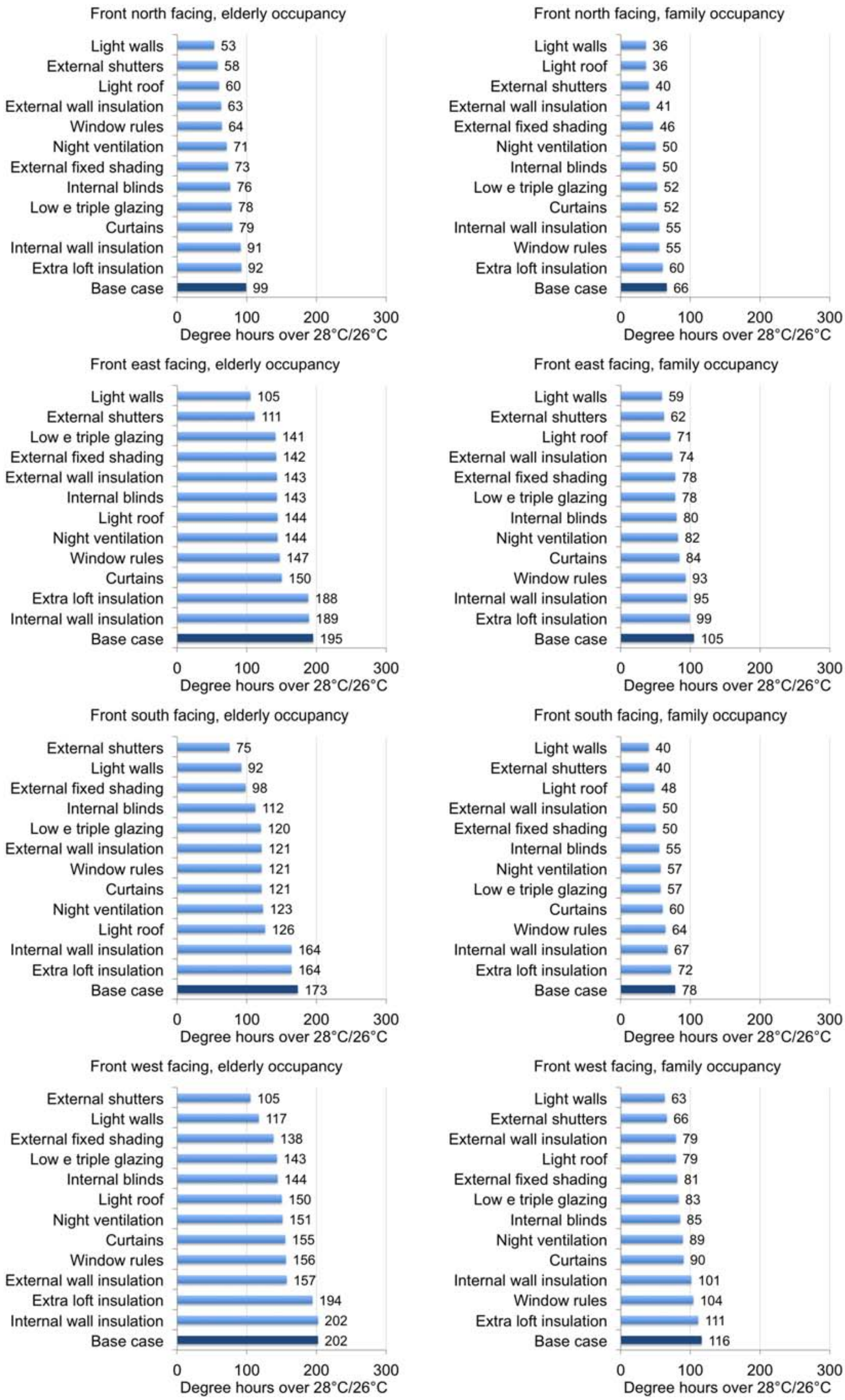

Figure 8.6 – Mid-terraced house total overheating - single interventions

The mid-terraced house experienced the lowest base case living room overheating of all the dwelling types, with the north-facing living room assuming family occupancy only recording 6 degree hours over 28 °C for the heat wave period. The internal temperatures were much lower than the outdoor temperature during the peak day-time hours, resulting in the high ranking of the window rules intervention, which was able to eliminate overheating for the north-facing living room with family occupancy and reduce overheating by 85% for elderly occupants. Night ventilation was slightly more effective than in the end-terraced house, reducing total overheating by 22-29%.

Increasing the thickness of the loft insulation had a slightly greater effect than in the end-terraced house, with reductions in total overheating of 8% for the north and south-facing main bedroom for both occupancy profiles.

8.2.2 Semi-detached house

The semi-detached house had uninsulated cavity walls, therefore cavity wall insulation was added as an intervention. Unlike the terraced houses, both the living room and main bedroom faced the same direction and were at the front of the house (see the floor plans in Figure 3.6). Figures 8.7 - 8.9 contain the overheating ranking charts for the semi-detached house.

External shutters were the highest ranked intervention for total overheating reduction for all orientations and both occupancy profiles (it was the equal highest ranked for south and east-facing with family occupancy), reducing overheating by 51-59%. The living room and main bedroom both had bay windows, therefore even for the north-facing orientation there were sections of glazing facing east and west, which benefited from the addition of shutters.

External fixed shading was very effective with the larger glazed area of the bay windows, reducing overheating in the south-facing living room by 65% for elderly occupants and 67% for the family profile. It was the equal highest ranked intervention for total overheating reduction (55%) for the south-facing orientation with family occupancy. For south-facing windows the fixed shading was not only effective in shielding the glazing from the high altitude sun, but also shielded some of the brickwork, reducing solar heat gains through the wall fabric.

The cavity wall construction did not conduct the solar heat gains as efficiently as the solid walls in the terraced houses, although interventions that shielded or reflected solar radiation from the external walls were still beneficial for overheating reduction. The light walls intervention reduced total overheating by 39-53%, with the greatest reduction when the front of the house was facing east. In this case the end (non-party) wall was south-facing.

External wall insulation reduced overheating in all cases, although to a lesser extent than in the terraced houses. The greatest reduction was observed for the south-facing orientation, where total overheating was reduced by 23% for elderly occupancy and 30% for family occupancy. Internal wall insulation reduced total overheating by 6% (elderly) and 13% (family) for the south-facing orientation and by less than 1% (elderly) and 6% (family) for the east-facing orientation. However, for the north and west-facing house, internal wall insulation increased the total overheating by 8% and 12% respectively for the elderly occupants. Cavity wall insulation also increased overheating by 3% for the west-facing orientation with elderly occupancy. In all cases cavity insulation was ranked between external and internal wall insulation.

The window rules intervention reduced overheating in the living room by up to 20% for elderly occupants, but was less effective for family occupants, who were out of the house during the hottest periods. Night ventilation was very effective for the living room in all cases, reducing overheating by 26-36% and total overheating by up to 30%.

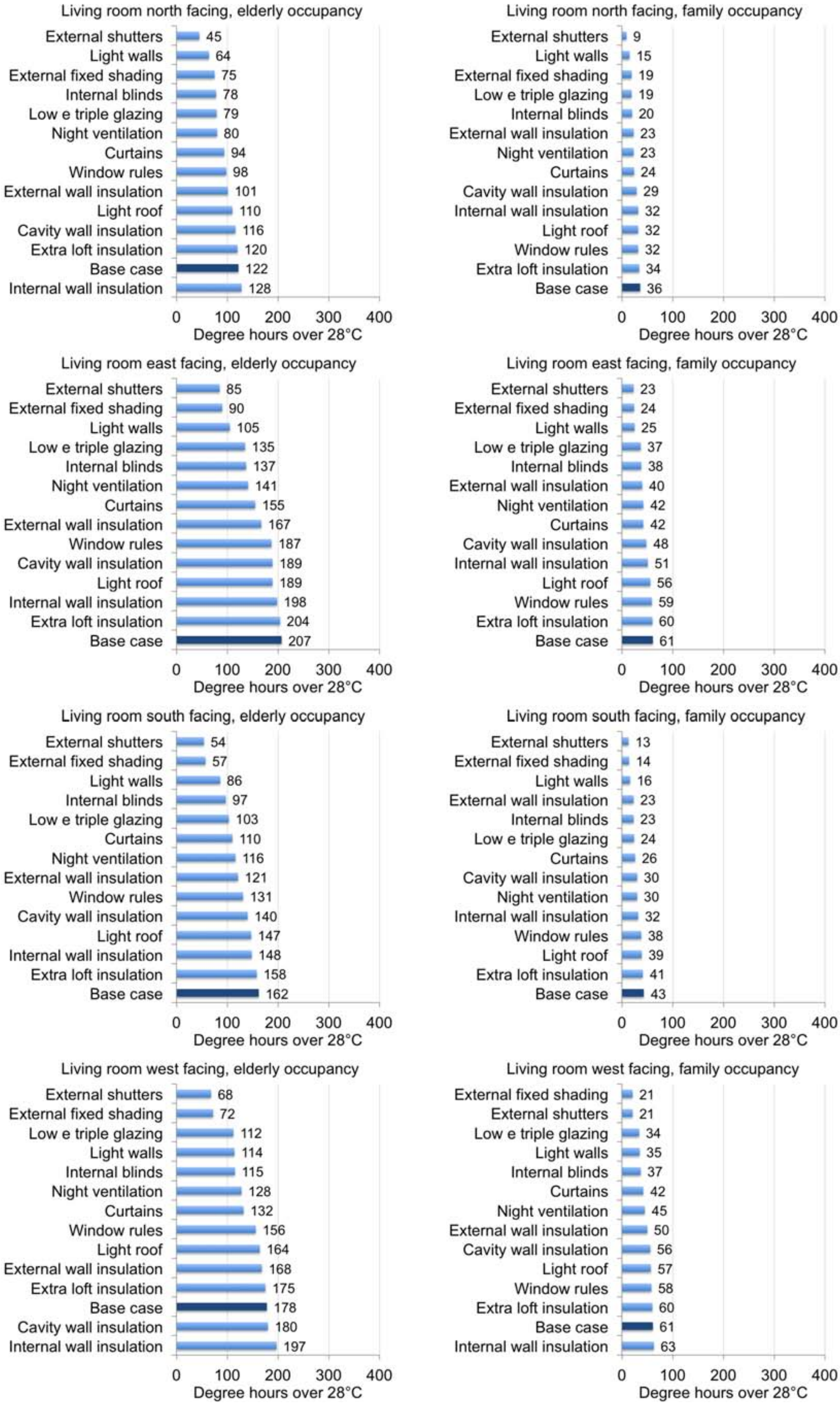

Figure 8.7 – Semi-detached house living room overheating - single interventions

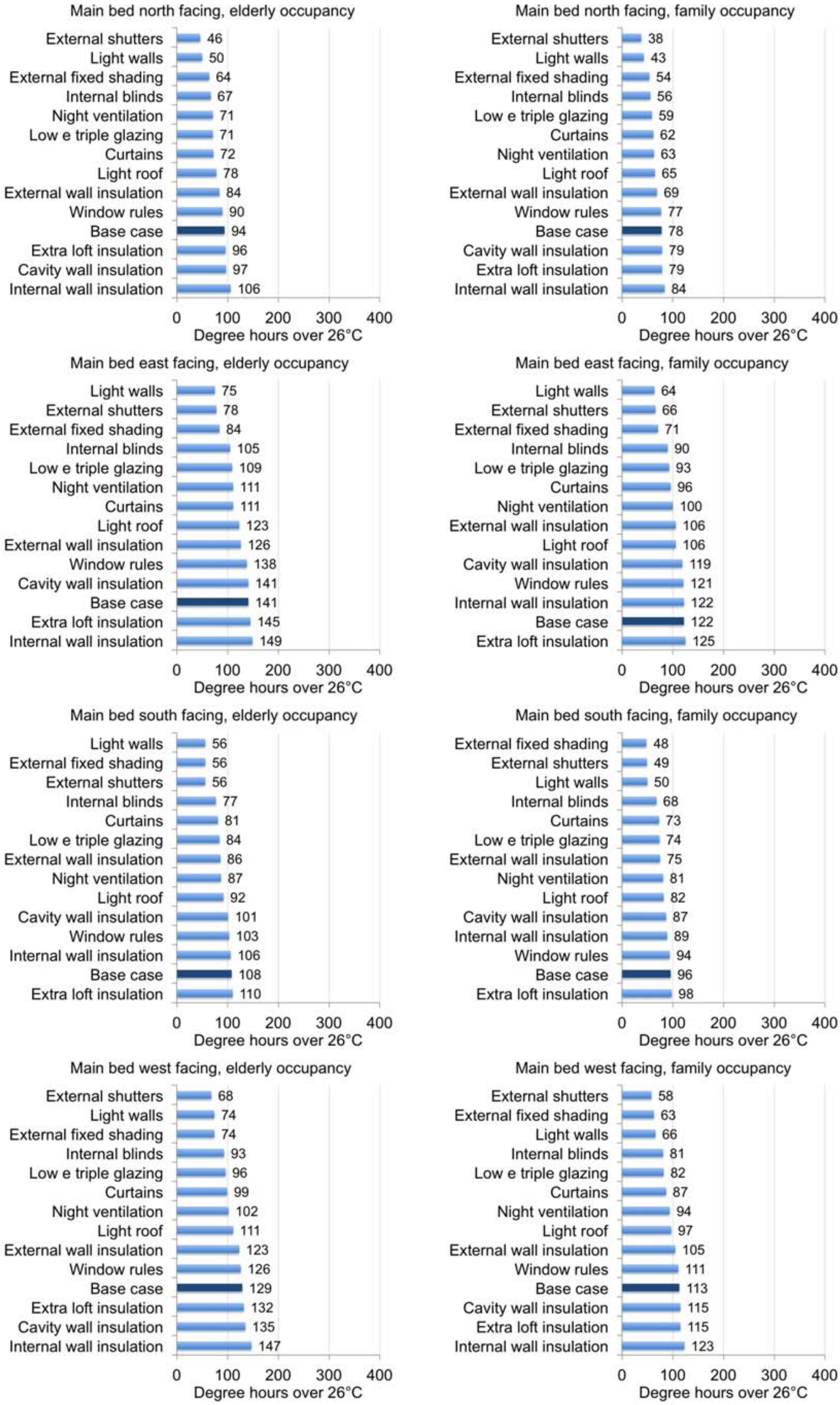

Figure 8.8 – Semi-detached house main bedroom overheating - single interventions

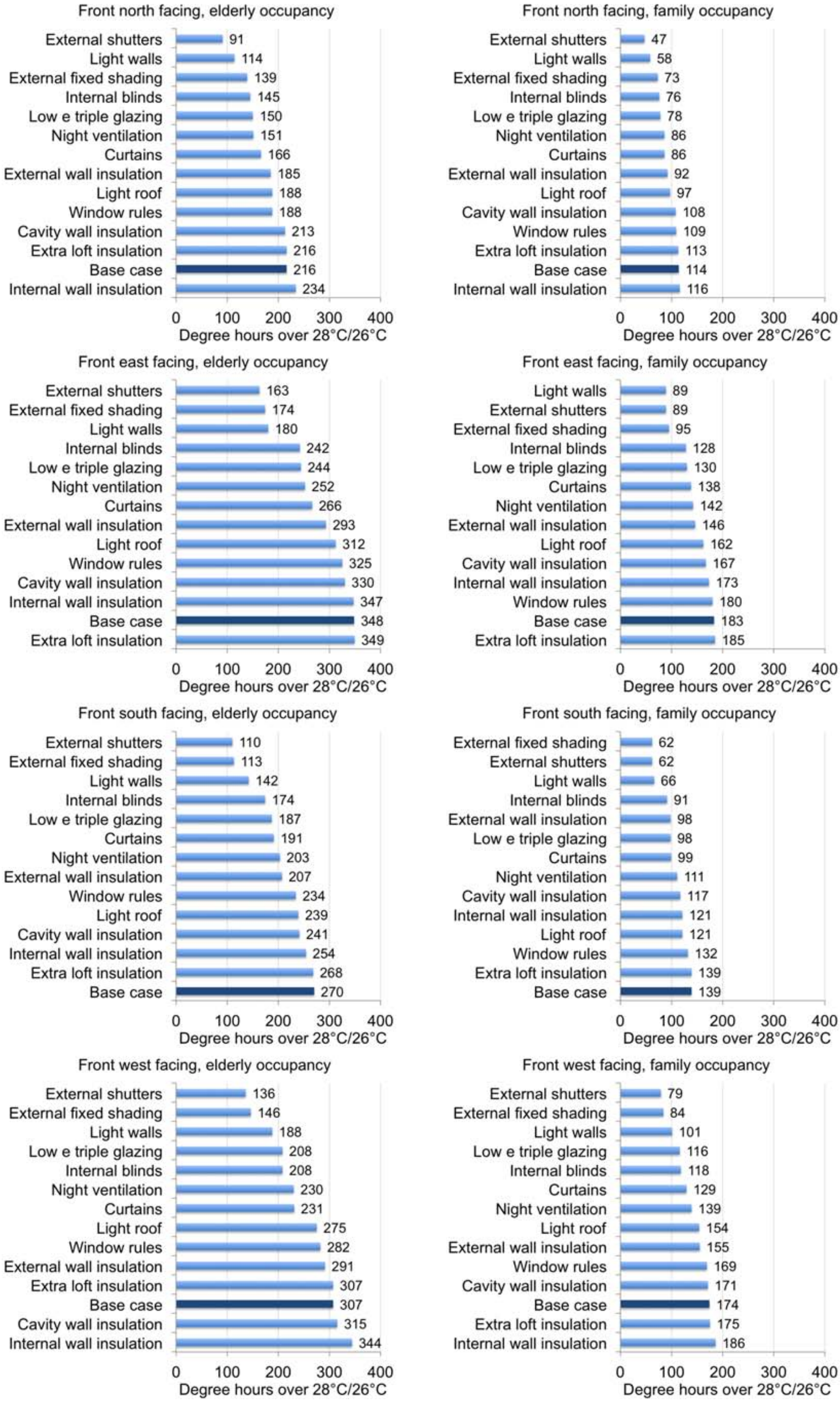

Figure 8.9 – Semi-detached house total overheating - single interventions

Low e triple-glazing was most effective for west-facing windows and reduced total overheating by 32% (elderly) and 33% (family), although variations in performance between orientations were small. When the front of the semi-detached house faced north, the glazed patio doors in the dining room faced south and solar heat gains through the glazing were convected through the open internal doors. Therefore interventions that reduced glazing solar heat gains for all orientations were effective.

Increasing the thickness of the loft insulation slightly increased bedroom overheating (by up to 2%), but the effect on total overheating was less, being either zero or up to 1% greater (east and west-facing with family occupancy).

8.2.3 Flats

The block of flats had identical room layouts for each storey (Figure 3.9), with the living room and main bedroom at the rear. The main bedroom also had a second external end wall. In common with the semi-detached house, the flats were assumed to have uninsulated cavity walls and the same set of interventions was considered. The top floor flat results were discussed in Chapter 7, this section presents the results for the ground and first (mid) floor flats.

8.2.3.1 Ground floor flat

The ground floor flat experienced significantly lower overheating than the first or top floor flats, being comparable to the mid-terraced house for total overheating for elderly occupants and experiencing the lowest total overheating for the family profile when the living room and main bedroom faced north. Figures 8.10 - 8.12 contain the overheating ranking charts for the living room, main bedroom and total overheating for the ground floor flat.

The large glazed area (particularly in the living room) resulted in external shutters always being the best intervention for both living room and total overheating reduction. Installation on south-facing windows was most effective, reducing overheating by 78-81%. For the main bedroom the light walls intervention was slightly more effective than shutters for the north and west facing orientations, reducing overheating for the family occupants by 81% when the window faced north (in which case the end wall faced west).

The flat windows were wide, but not very tall (1.1m) and the external fixed shading was very effective at shielding most of the glazing from direct solar radiation. It was particularly effective for the south-facing living room, where overheating was reduced by 78% (elderly) and 83% (family) and was ranked second below shutters. It was also the second ranked intervention for total overheating when windows faced south, east or west for both occupancy profiles.

The large glazed area also resulted in low e triple-glazing being very effective, reducing total overheating by 53% (family) and 49% (elderly) when the windows at the front of the flat faced west and the living room and main bedroom windows faced east.

External wall insulation always performed better than internal or cavity wall insulation for overheating reduction, reducing total overheating by 11-35% (elderly) and 16-55% (family). For both occupancy profiles the greatest reduction was achieved for north-facing living room and main bedroom windows. In this case the unglazed end wall was west-facing and the front of the block faced south. In the living room, internal wall insulation increased overheating by up to 10% compared to the base case flat in all but one case (south-facing windows with family occupancy). Cavity wall insulation was ranked between external and internal wall insulation for the living room, reducing overheating by up to 13% (north and south-facing windows with family occupancy), but causing a very slight increase (less than 1%) for east-facing windows with elderly occupancy.

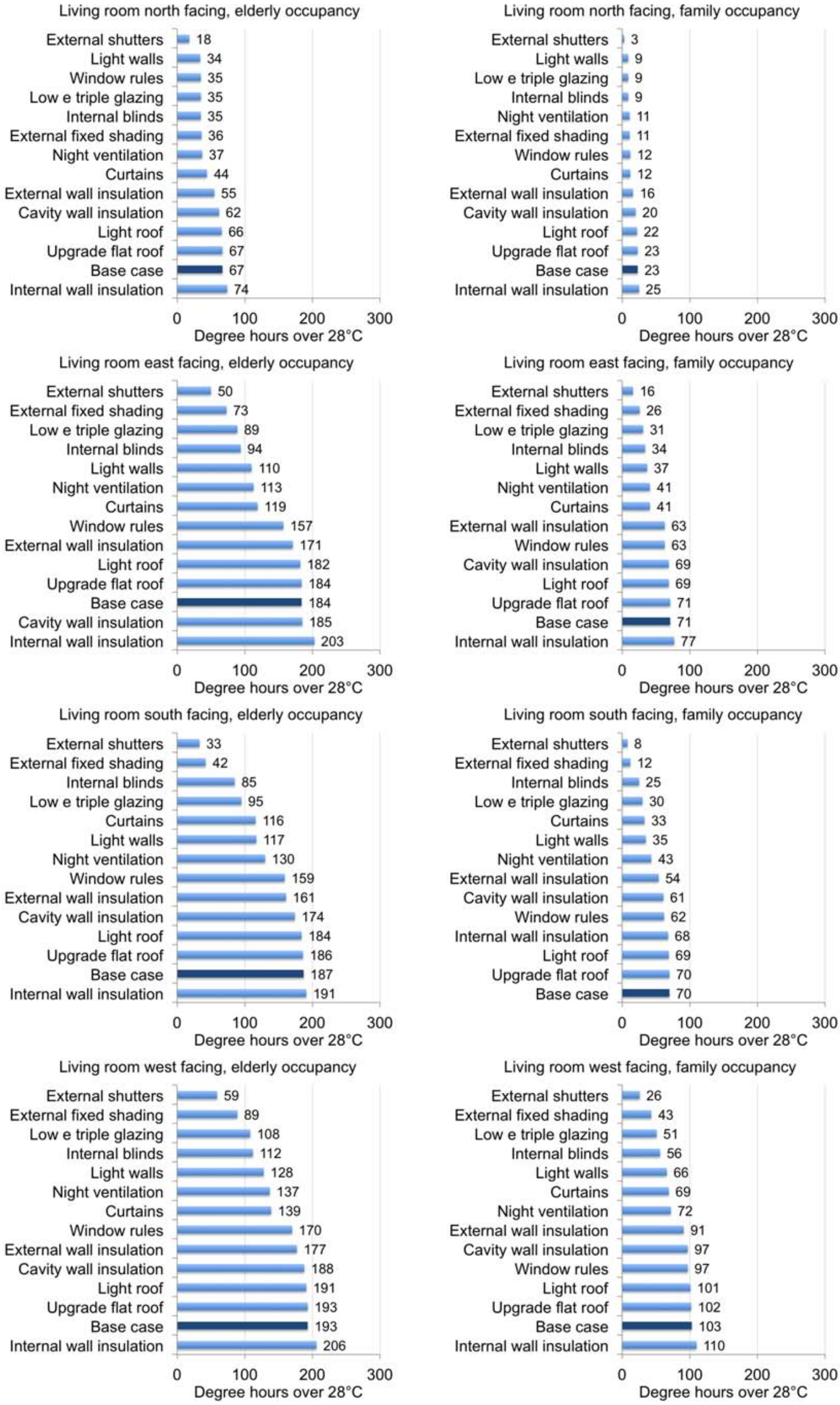

Figure 8.10 – Ground floor flat living room overheating - single interventions

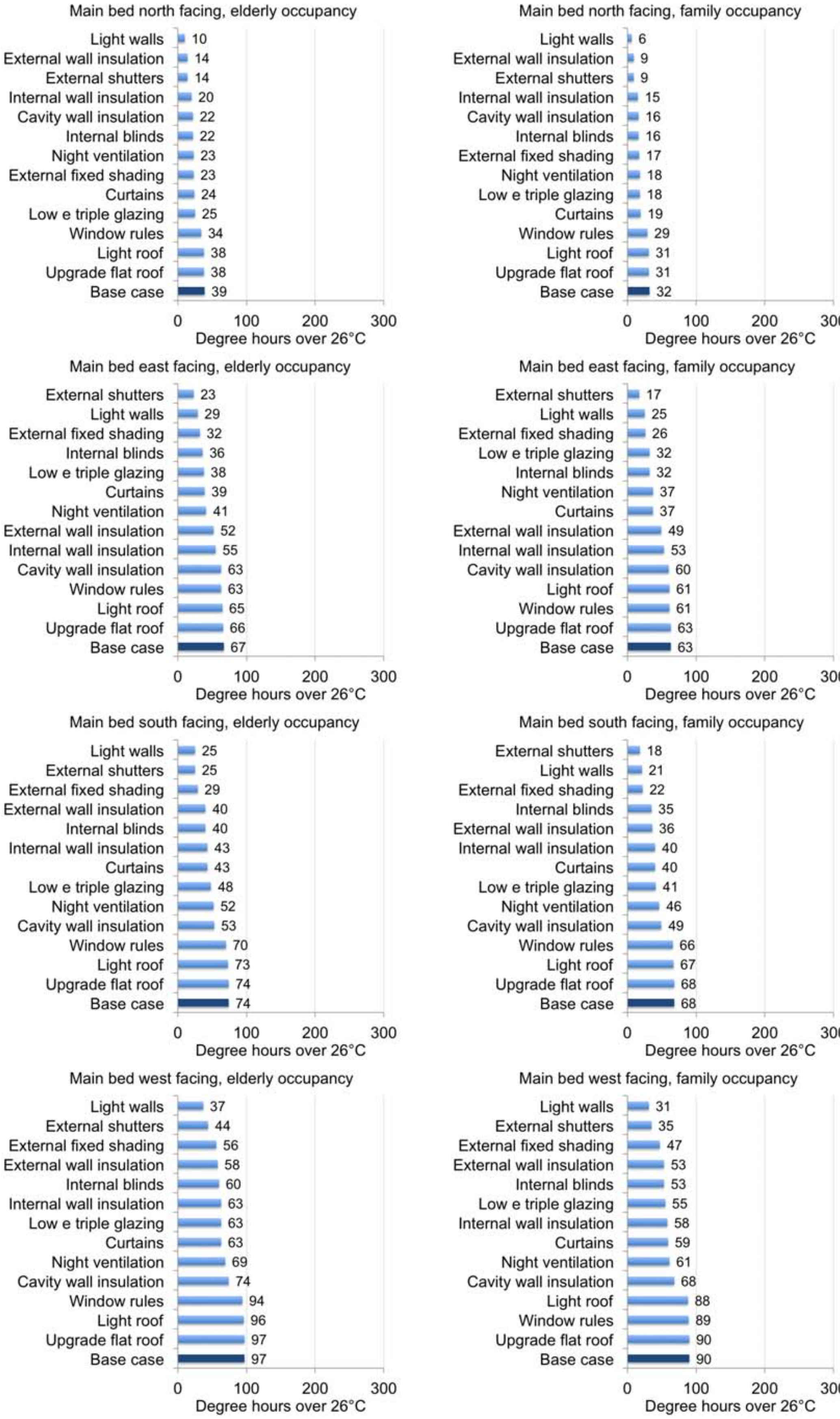

Figure 8.11 – Ground floor flat main bedroom overheating - single interventions

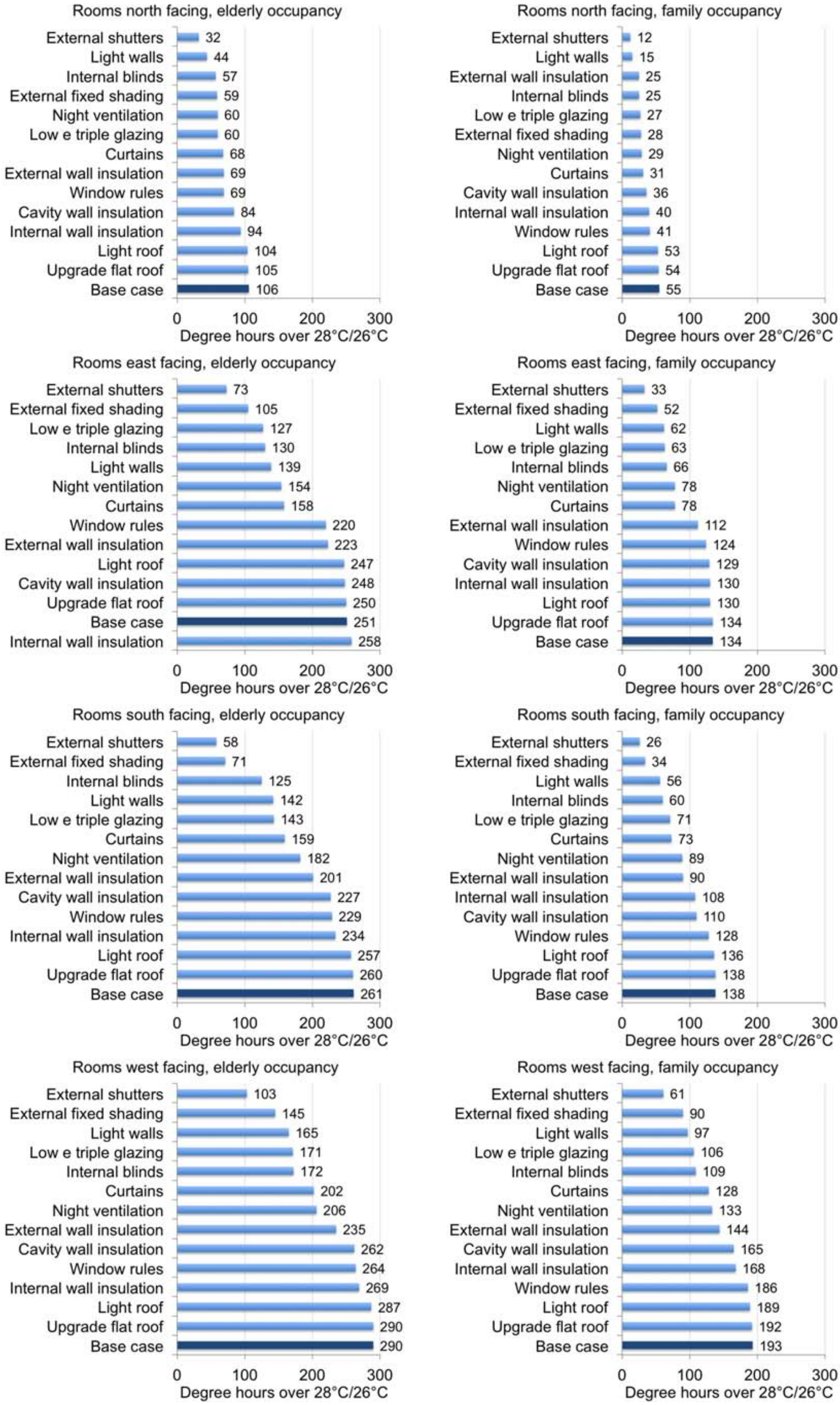

Figure 8.12 – Ground floor flat total overheating - single interventions

In common with the top floor flat results (Chapter7), the ranking order for wall insulation in the main bedroom was different. Cavity insulation was always the least effective for overheating reduction and external insulation the best, but none of the wall insulation interventions resulted in greater overheating than the base case flat. The smallest overheating reduction was seen for the east-facing main bedroom. In this case the end wall was north-facing and there were lower solar heat gains through the external walls for the insulation to reduce. Total overheating was only greater than the base case for one scenario: east-facing windows with elderly occupancy, where internal wall insulation increased overheating by 3%.

The window rules intervention varied significantly depending on orientation and occupancy profile. The percentage overheating reduction was greatest for the north-facing living room, where room temperatures were the lowest and therefore increased by the greatest percentage if the windows were opened during hot periods. The smallest overheating reduction was in the west-facing living room with family occupancy. In this case the room was unoccupied during the hottest part of the day, but afternoon solar heat gains raised the room temperature to be closer to the outdoor temperature by the time the room was occupied (from 4pm), reducing the temperature differential and hence the impact of the intervention.

Night ventilation reduced total overheating by 29-47%. It was more effective for north-facing rooms, where the benefit lasted in to the daytime and there were lower solar heat gains. For the family occupancy profile there were also no internal heat gains during the daytime and the living room remained cooler towards the evening occupied period.

Upgrading the flat roof with a greater level of insulation or coating the roof with solar reflective paint (light roof) had very little effect on ground floor flat overheating.

8.2.3.2 First floor flat

Unlike the ground floor flat, the first floor flat did not have the cooling benefit of a solid (uninsulated) ground floor and had occupied rooms both above and below. Overheating was significantly higher than the ground floor flat (two and a half times more for the worst case: west-facing windows with elderly occupancy). Figures 8.13 - 8.15 contain the overheating ranking charts for the first floor flat.

External shutters were again the highest ranked intervention for total overheating reduction for all orientations, reducing degree hours by 58% for the south-facing living room and main bedroom. Shutters were also the most effective intervention for the living room in all cases and for the main bedroom facing south or east. In common with the ground floor flat, the light walls intervention was the highest ranked intervention for the north and west-facing main bedroom, reducing overheating by up to 52% (north-facing with family occupants).

External fixed shading was ranked second for both living room and total overheating reduction for south, east and west-facing windows, for both occupancy profiles, reducing south-facing living room overheating for elderly occupants by 57%.

Low e triple-glazing consistently reduced total overheating by 26-32% and, in common with the ground and top floor flats, was most effective for east-facing living room and main bedroom windows (with windows at the front of the building facing west).

External wall insulation was the highest ranked of the three wall insulation types for overheating reduction in all cases. For the south, west and north-facing living room the addition of external wall insulation always reduced overheating for family occupants and only increased overheating by 1% for elderly occupants in the west-facing living room. The greatest reduction in total overheating was for the south-facing living room and main bedroom, where external wall insulation reduced overheating by 8% (elderly) and 12% (family). For the east-facing living room however, external

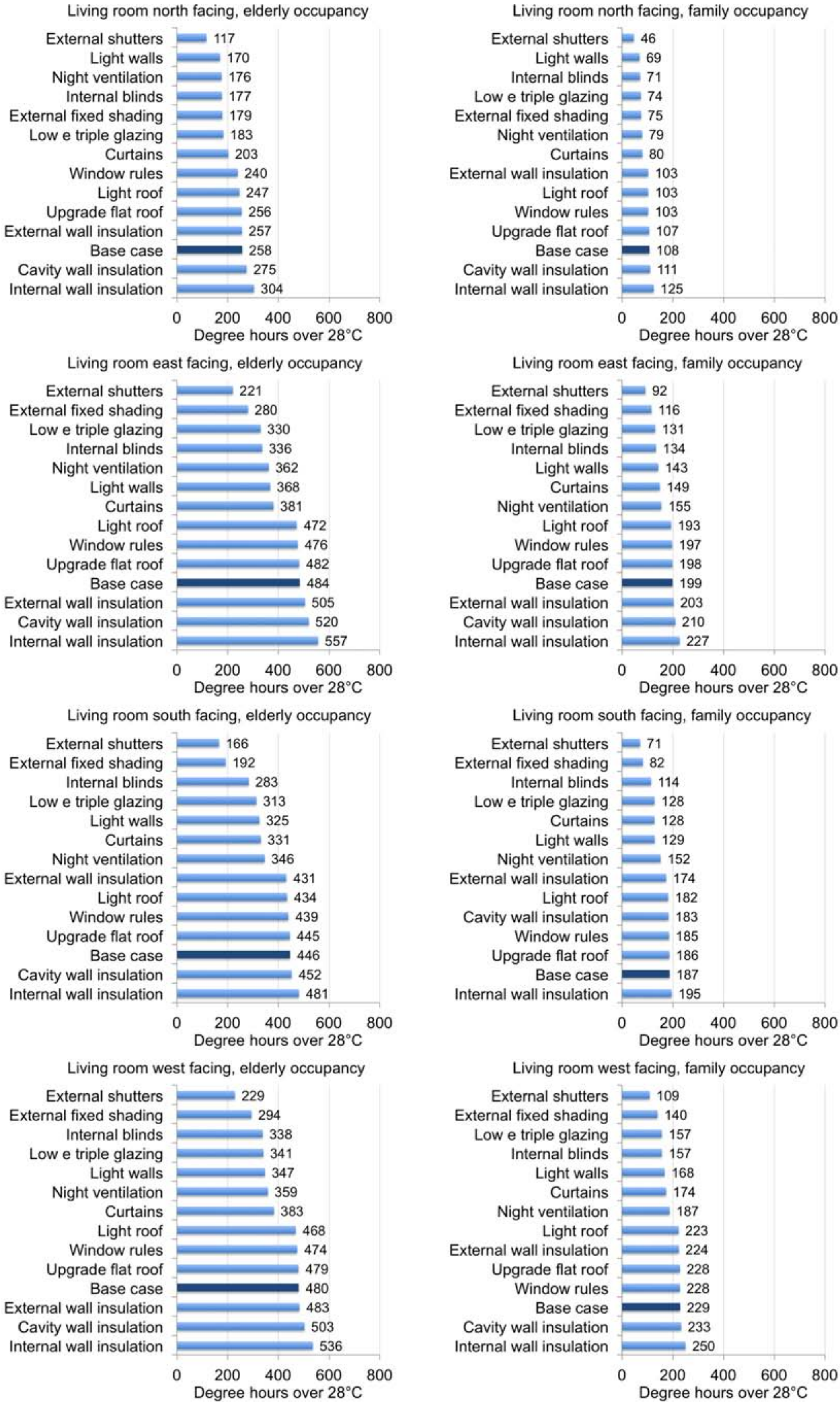

Figure 8.13 – First floor flat living room overheating - single interventions

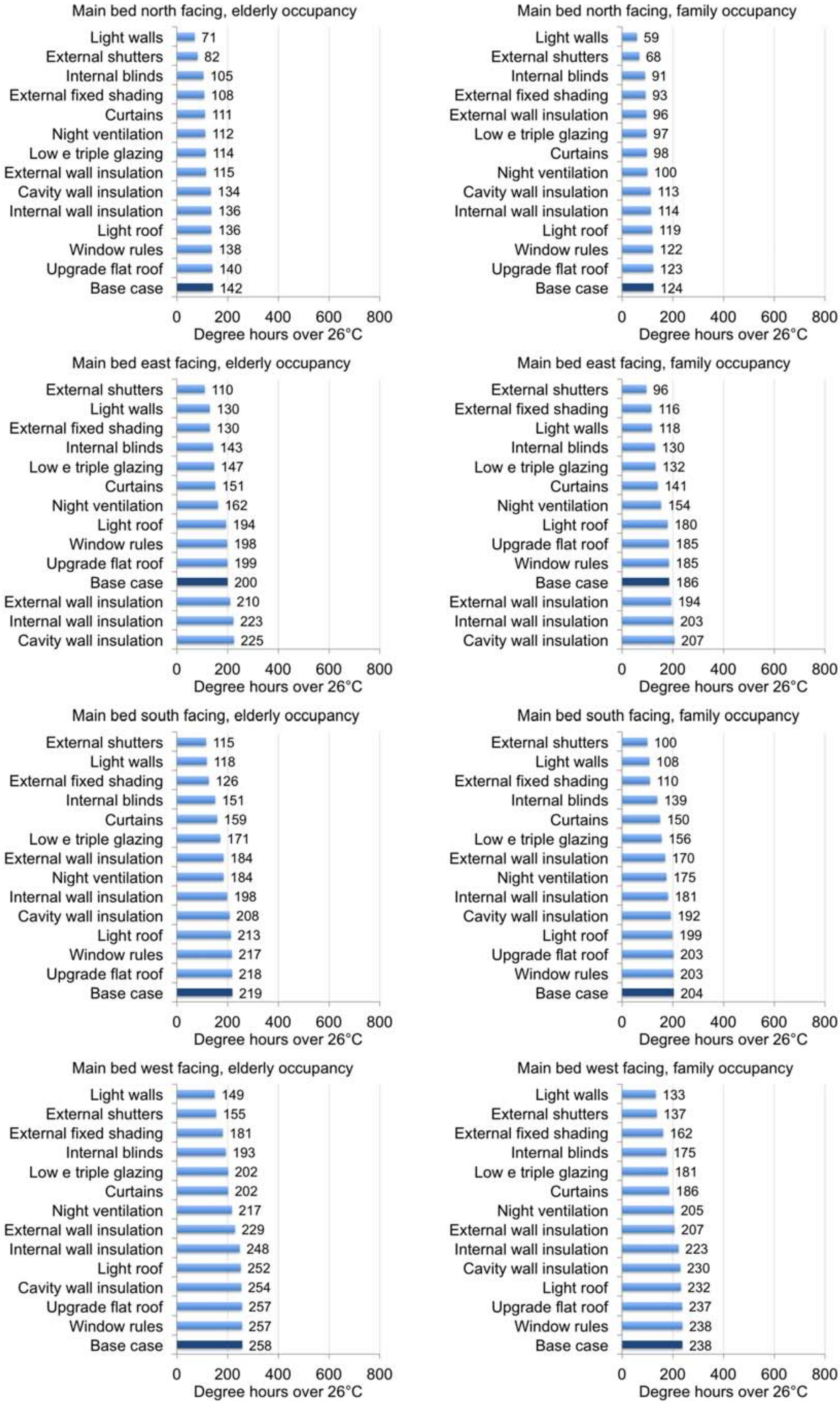

Figure 8.14 – First floor flat main bedroom overheating - single interventions

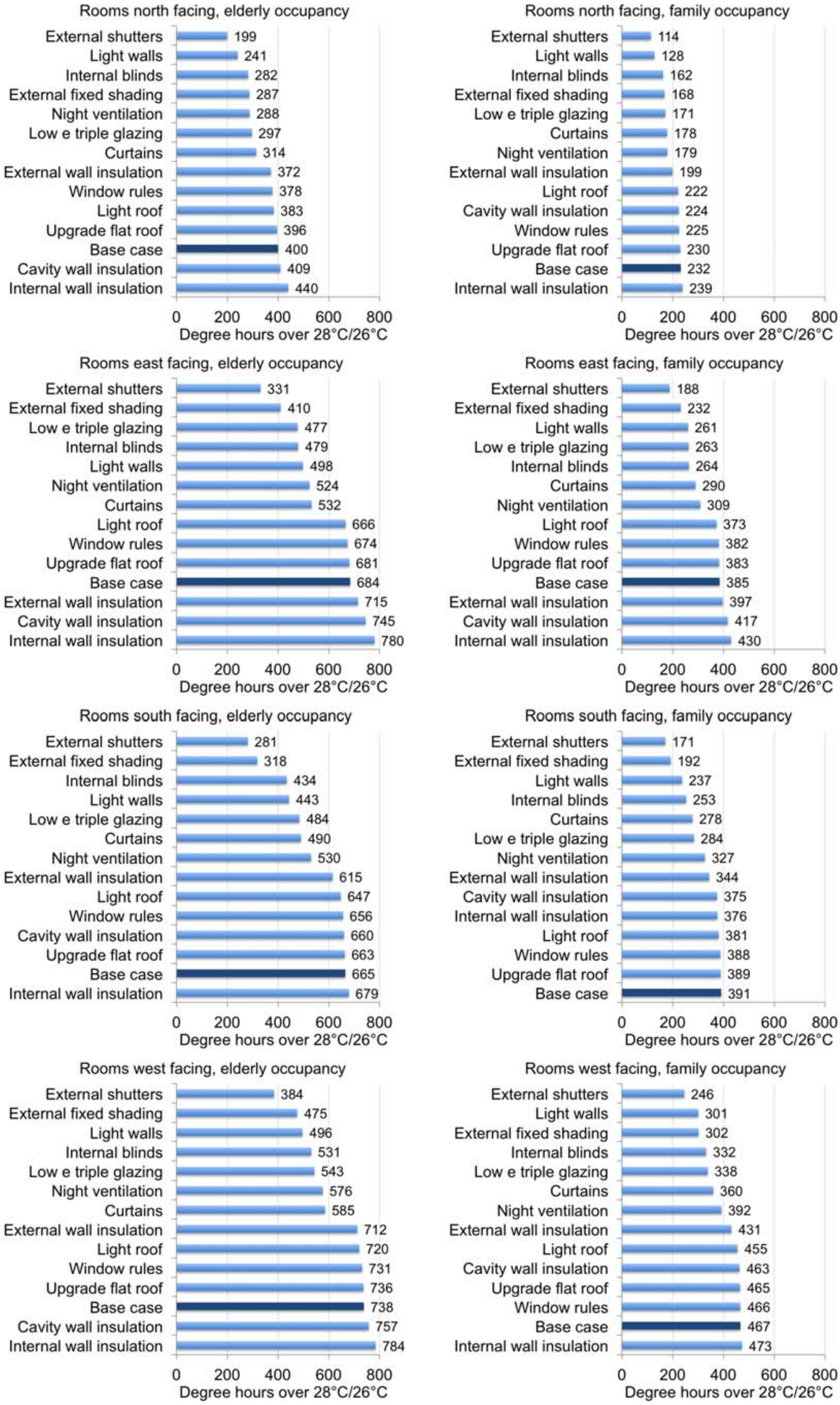

Figure 8.15 – First floor flat total overheating - single interventions

wall insulation increased overheating for both the living room and main bedroom and increased total overheating by 5% for elderly occupants.

Internal wall insulation always increased overheating in the living room and increased overheating by 18% for elderly occupants when the windows were north-facing. Internal wall insulation also produced the greatest increases in total overheating, with east-facing rooms experiencing increases of 12% (family) and 14% (elderly).

Cavity wall insulation reduced main bedroom overheating for south, west and north-facing windows, but resulted in the greatest overheating for east-facing windows, where overheating increased by 11% (family) and 13% (elderly).

The window rules intervention was much less effective compared to the ground floor flat. Room temperatures in the first floor flat were closer to the outdoor air temperature during the hottest periods. The greatest overheating reduction (7%) was for elderly occupants in the north-facing living room. For the other orientations overheating reduction was minimal (1-2%). Night ventilation was less effective than was the case for the ground floor flat, but slightly more effective than in the top floor flat. The largest reduction was when the living room and main bedroom faced north, where total overheating was reduced by 28% for elderly occupants.

In common with the ground floor flat, the flat roof interventions (upgrading the flat roof and light roof) had very little effect on overheating.

8.2.4 Detached house

The detached house experienced similar total overheating to the first floor flat. In common with the terraced houses, the living room and main bedroom are at opposite sides of the house, with the main bedroom at the front and the living room at the rear (floor plans, Figure 3.12). Unlike the other dwellings the modern construction of the detached house had well insulated walls and loft space. Wall and loft insulation interventions were therefore not considered. Figures 8.17 - 8.19 contain the overheating ranking charts for the detached house.

None of the interventions increased overheating, either for the living room or the main bedroom. The highest ranked intervention in all cases was external shutters, which reduced overheating by 67% for the south-facing living room assuming elderly occupancy. External fixed shading was the second ranked intervention for the south, east and west-facing living room for both occupancy profiles and reduced overheating in the south-facing living room with elderly occupancy by 44%. Low e triple-glazing reduced total overheating by 30-33% and was comparable in performance to internal blinds.

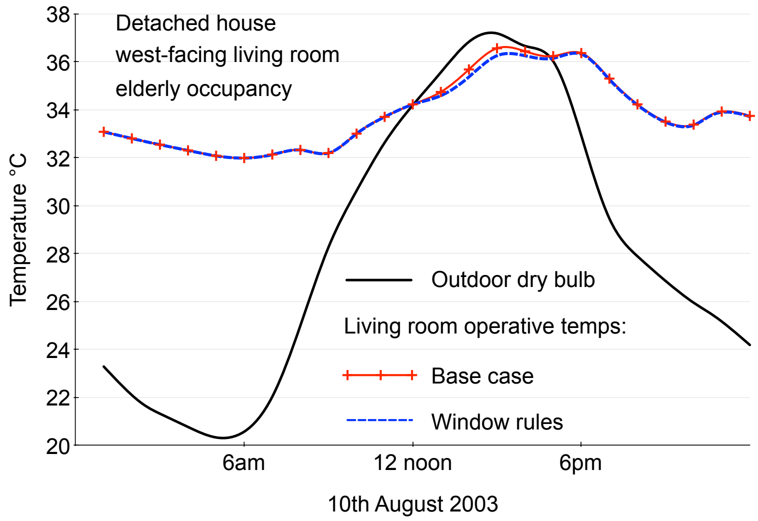

Figure 8.16 – Detached house heat wave day living room temperature

The light walls intervention was less effective than in the other dwelling types due to the highly insulated walls, producing at best a 20% reduction in total overheating for the front south-facing orientation. In this case the living room also had a west-facing second external wall and the main bedroom an east-facing second external wall.

The room temperatures during the hottest periods were close to the outdoor temperature, resulting in the window rules intervention having very little effect, even

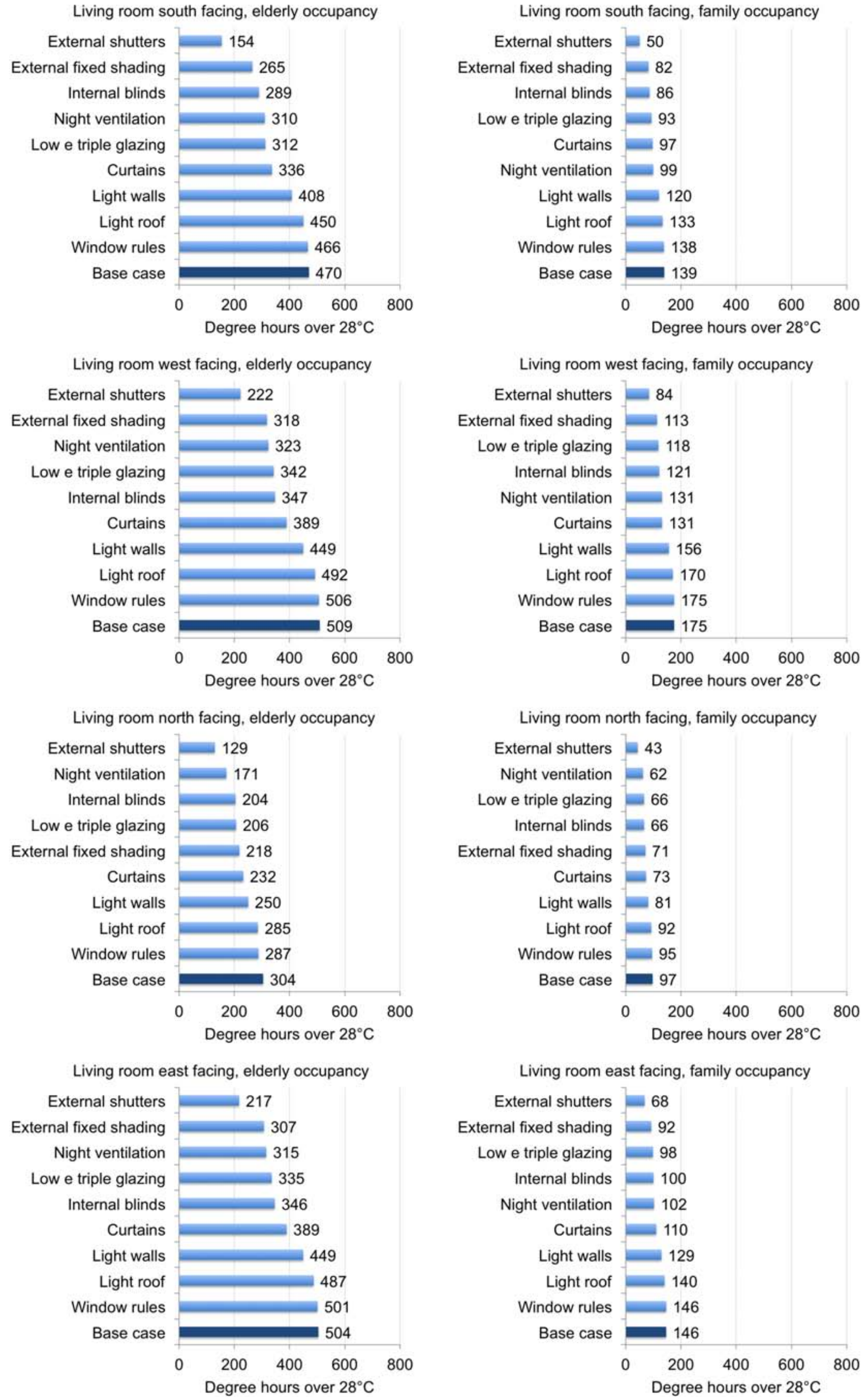

Figure 8.17 – Detached house living room overheating - single interventions

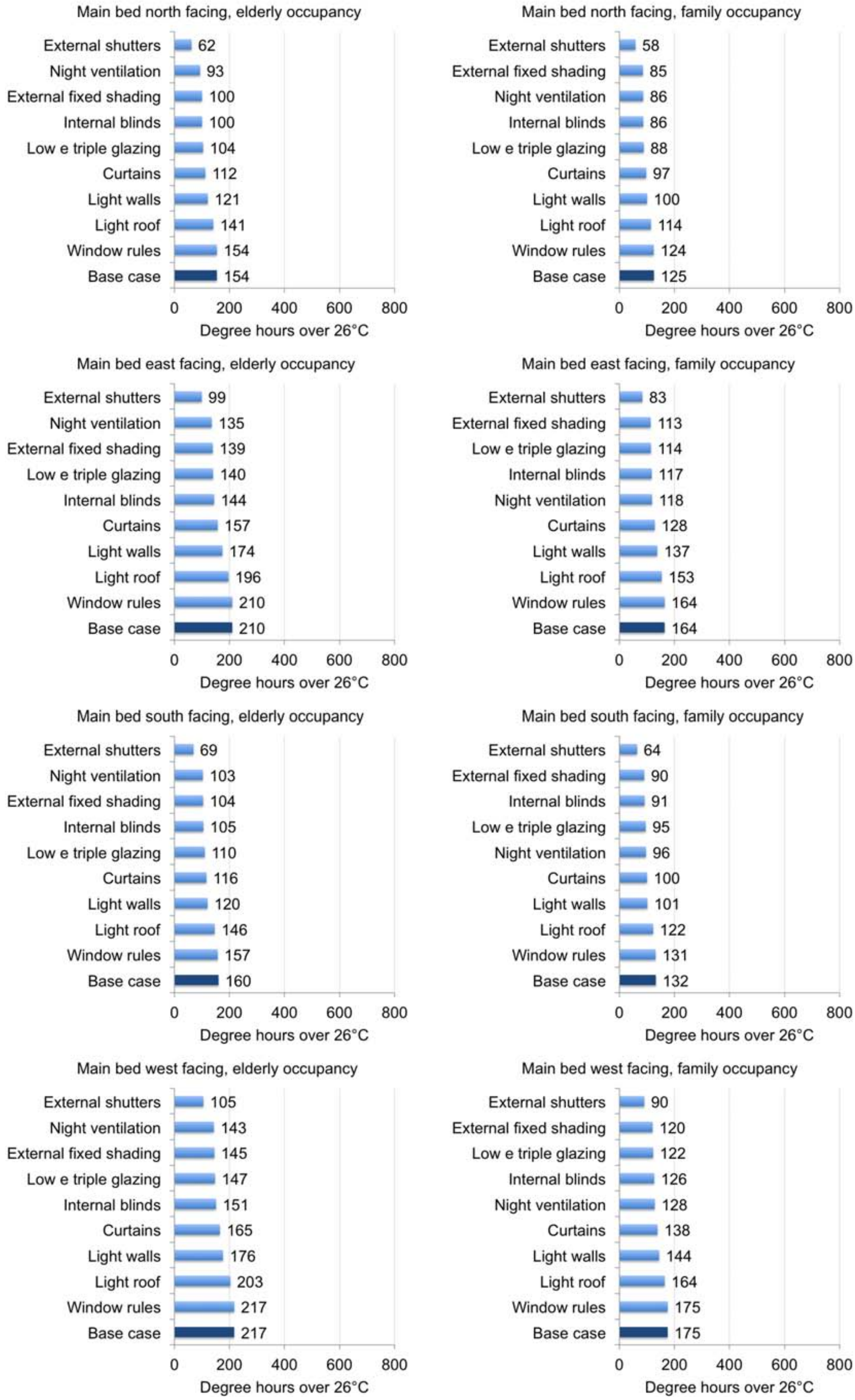

Figure 8.18 – Detached house main bedroom overheating - single interventions

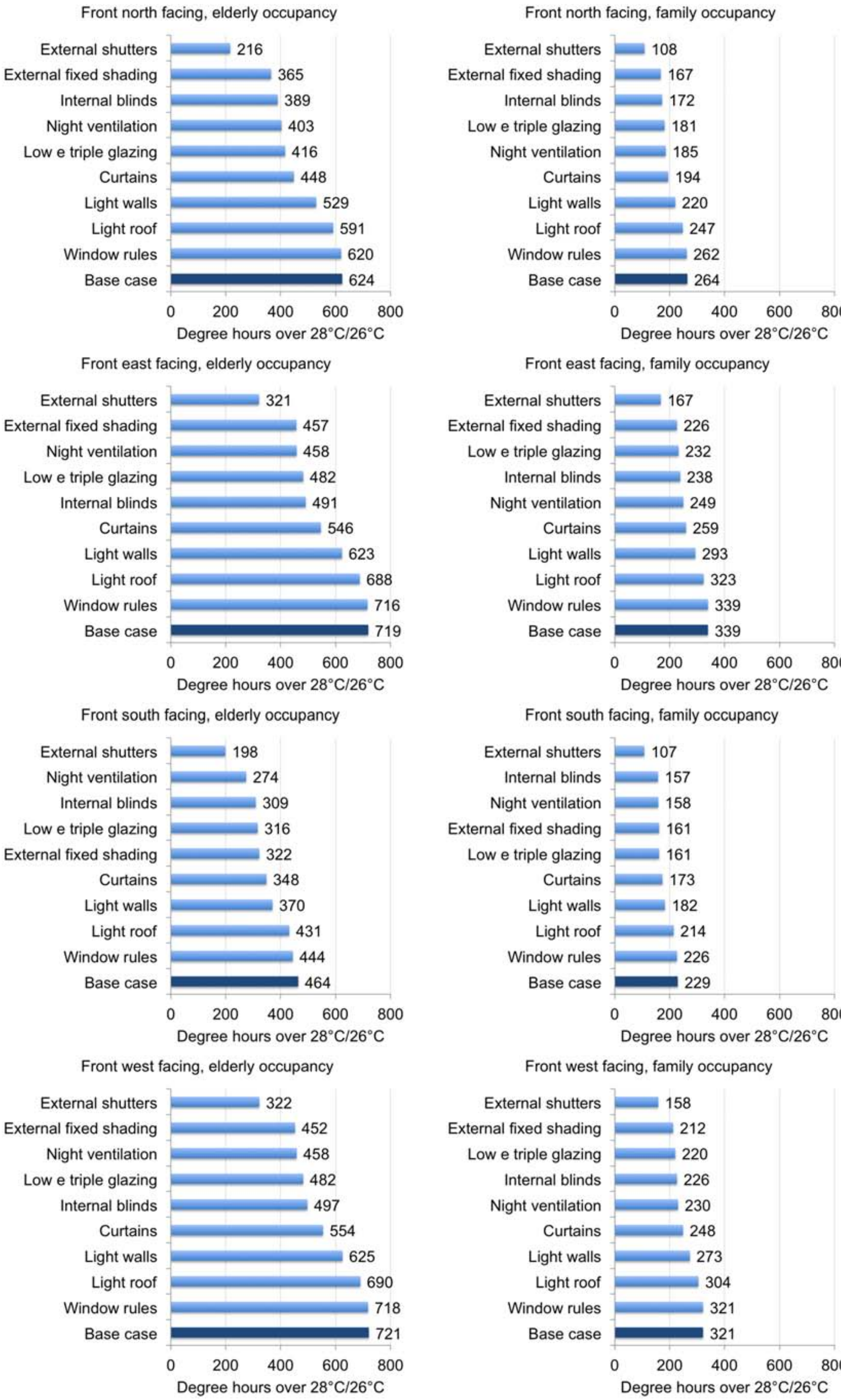

Figure 8.19 – Detached house total overheating - single interventions

for elderly occupants in the living room during the daytime (Figure 8.16). Night ventilation, however, was very effective, reducing total overheating by 27-41% and living room overheating by up to 44% (north-facing with elderly occupancy).

The light roof intervention was less effective in the detached house than in the other dwellings due to the higher level of loft insulation in the base case house, but still reduced total overheating by between 4% and 7%.

8.3 Effect of interventions on heating energy use

The space heating energy use associated with each intervention was modelled in EnergyPlus using the current London Heathrow TRY weather file (Section 5.6). Insulation interventions reduced heating energy use, with internal and external wall insulation having the greatest effect. Solar control interventions that were fixed and therefore in use all-year-round, such as the light roof and walls and external fixed shading interventions, resulted in greater heating energy use due to the loss of beneficial solar heat gains during the heating seasons. Low e triple-glazing has a lower U-value than the base case double-glazing, which reduced heating energy use, but the low e coatings reduced solar heat gains both in the summer and during the heating seasons. The net effect for the terraced houses, flats and semi-detached house was a very small decrease, or occasionally a small increase, in heating energy use depending on orientation.

In the case of the detached house, the default (2006 building regulations) low e coated double-glazing had a high SHGC and was effective in retaining heat gains within the dwelling. Fitting low e triple-glazing with a low SHGC resulted in significant increases in heating energy use (up to 12.5%) for the modern detached house. The base case heating energy use for each dwelling was presented in Table 6.1. Tables 8.1-8.6 show the percentage change in heating energy use associated with each intervention for the modelled dwellings (the top floor flat results are presented in Table 7.2 in Chapter 7). Only those interventions that affect heating energy use have been included in the tables. Internal blinds, curtains and external shutters were assumed to be left open during the daytime in the heating seasons and the ventilation strategies were also assumed to only be used when required in hot weather.

Combining the interventions resulted in the effect on heating energy use being either partially cancelled out or compounded to produce greater increases or reductions, which is discussed in Section 8.4.

	Heating energy use change from base case %							
	Elderly occupancy profile				Family occupancy profile			
	Front of house facing				Front of house facing			
Intervention	North	East	South	West	North	East	South	West
Low e triple glazing	-0.6	-0.1	+0.2	-0.5	-0.6	-0.1	+0.2	-0.6
External fixed shading	+1.0	+1.8	+1.8	+1.1	+1.1	+1.8	+1.7	+1.1
Loft insulation	-2.1	-2.1	-2.2	-2.0	-2.5	-2.6	-2.6	-2.5
Light roof	+2.7	+2.6	+2.4	+2.6	+2.7	+2.7	+2.4	+2.5
Light walls	+7.1	+8.6	+6.3	+4.9	+7.9	+9.4	+6.9	+5.2
External wall insulation	-44.6	-45.0	-46.4	-45.5	-46.8	-47.2	-48.7	-47.7
Internal wall insulation	-44.8	-45.2	-46.6	-45.7	-47.0	-47.2	-48.8	-47.9

Table 8.1 – Effect of interventions on space heating energy use: End-terraced house

	Heating energy use change from base case %							
	Elderly occupancy profile				Family occupancy profile			
	Front of house facing				Front of house facing			
Intervention	North	East	South	West	North	East	South	West
Low e triple glazing	-1.1	-0.8	-0.1	-0.6	-0.9	-0.8	0	-0.6
External fixed shading	+1.3	+1.5	+2.4	+2.0	+1.4	+1.5	+2.5	+2.0
Loft insulation	-2.7	-2.8	-2.9	-2.8	-3.1	-3.2	-3.3	-3.3
Light roof	+3.3	+3.2	+3.2	+3.2	+3.3	+3.2	+3.2	+3.1
Light walls	+4.2	+4.2	+4.7	+4.4	+4.7	+4.6	+5.2	+4.9
External wall insulation	-37.1	-37.6	-38.5	-37.7	-39.6	-40.1	-41.0	-40.1
Internal wall insulation	-37.2	-37.7	-38.5	-37.8	-39.8	-40.2	-41.1	-40.1

Table 8.2 – Effect of interventions on space heating energy use: Mid-terraced house

Intervention	Heating energy use change from base case %							
	Elderly occupancy profile				Family occupancy profile			
	Front of house facing				Front of house facing			
	North	East	South	West	North	East	South	West
Low e triple glazing	-0.2	-1.3	-1.4	-1.3	-0.5	-1.5	-1.7	-1.6
External fixed shading	+4.8	+3.6	+5.0	+2.9	+4.2	+3.1	+4.6	+2.7
Loft insulation	-3.6	-3.6	-3.5	-3.5	-3.8	-3.9	-3.8	-3.8
Light roof	+1.5	+1.3	+1.5	+1.4	+1.3	+1.2	+1.2	+1.1
Light walls	+9.1	+10.2	+8.2	+6.5	+9.2	+10.4	+8.3	+6.7
External wall insulation	-41.8	-39.6	-40.1	-40.7	-41.4	-38.8	-39.6	-40.3
Internal wall insulation	-41.7	-39.5	-40.2	-40.7	-40.8	-38.1	-39.0	-39.7
Cavity wall insulation	-31.6	-29.9	-30.3	-30.8	-30.9	-29.0	-29.6	-30.2

Table 8.3 – Effect of interventions on space heating energy use: Semi-detached house

Intervention	Heating energy use change from base case %							
	Elderly occupancy profile				Family occupancy profile			
	Front of house facing				Front of house facing			
	North	East	South	West	North	East	South	West
Low e triple glazing	+11	+8.2	+9.4	+7.9	+12.5	+8.1	+9.8	+8.1
External fixed shading	+7.0	+6.8	+5.8	+6.8	+7.7	+6.6	+5.7	+7.0
Light roof	+1.5	+1.1	+1.4	+1.1	+1.6	+0.7	+1.5	+1.1
Light walls	+4.9	+4.6	+5.3	+4.6	+5.6	+4.8	+5.7	+4.8

Table 8.4 – Effect of interventions on space heating energy use: Detached house

Intervention	Heating energy use change from base case %							
	Elderly occupancy profile				Family occupancy profile			
	Front of block facing				Front of block facing			
	North	East	South	West	North	East	South	West
Low e triple glazing	+0.2	-1.6	-0.9	-1.2	+0.8	-1.3	-0.8	-0.8
External fixed shading	+9.4	+7.8	+6.6	+8.1	+9.6	+7.3	+5.8	+7.8
Upgrade flat roof	-0.1	-0.1	-0.1	-0.1	-0.1	-0.3	-0.1	-0.1
Light roof	+0.1	+0.1	+0.1	+0.1	+0.1	0	+0.1	+0.1
Light walls	+9.4	+10.0	+8.9	+7.1	+9.7	+10.0	+8.9	+7.4
External wall insulation	-41.6	-38.4	-40.3	-39.9	-39.1	-35.6	-37.0	-37.3
Internal wall insulation	-41.6	-38.5	-40.5	-40.0	-38.9	-35.6	-37.0	-37.2
Cavity wall insulation	-34.4	-31.7	-33.3	-33.1	-31.9	-29.1	-30.2	-30.4

Table 8.5 – Effect of interventions on space heating energy use: Ground floor flat

Intervention	Heating energy use change from base case %							
	Elderly occupancy profile				Family occupancy profile			
	Front of block facing				Front of block facing			
	North	East	South	West	North	East	South	West
Low e triple glazing	-1.2	-3.5	-2.3	-2.9	0	-2.6	-1.6	-2.1
External fixed shading	+9.5	+7.5	+6.9	+7.7	+10.1	+7.5	+6.1	+7.7
Upgrade flat roof	-3.2	-2.9	-2.9	-2.9	-3.3	-3.1	-3.1	-3.0
Light roof	+1.3	+1.1	+1.4	+2.9	+1.7	+1.5	+1.6	+1.4
Light walls	+10.8	+11.1	+10.4	+7.7	+11.0	+11.3	+10.3	+7.9
External wall insulation	-51.4	-47.4	-50.4	-48.8	-49.1	-44.4	-46.9	-46.1
Internal wall insulation	-50.5	-46.8	-49.8	-48.1	-48.4	-43.9	-46.2	-45.4
Cavity wall insulation	-41.9	-38.6	-41.3	-39.8	-40.0	-36.1	-38.4	-37.6

Table 8.6 – Effect of interventions on space heating energy use: 1st floor flat

8.4 Combined interventions

The difficulty of presenting all of the combined interventions results was discussed in Chapter 7. The retrofit toolkit (Section 7.4, supplied on CD-ROM in Appendix B) should be used to visualise the full range of combined interventions results. The results tables in this section present the combined interventions that (a) reduce overheating by the greatest percentage at the lowest cost, regardless of the effect on space heating energy use and (b) reduce space heating energy use by the greatest amount at a given cost. However, within (b), there are often several intervention combinations that produce the lowest space heating energy reduction within a cost band. The combination that produces the greatest reduction in both energy use and overheating has been selected.

In each case the total overheating reduction has been selected, i.e. overheating for living room plus main bedroom for occupied periods. The cost bands have been set at zero; low (up to £5k); medium (£5k to £10k) and high (over £10k) to provide a range of intervention packages. Table 8.7 contains the key to the codes used for the interventions in Sections 8.4.1-8.4.4.

Code	Intervention
B	Internal blinds
S	External shutters
C	Curtains
LG	Low e triple glazing
FS	External fixed shading
NV	Night ventilation
WR	Window rules
UR	Upgrade flat roof
L	Loft insulation
LR	Light roof
LW	Light walls
EW	External wall insulation
IW	Internal wall insulation
CW	Cavity wall insulation

Table 8.7 – Key to intervention codes in Tables 8.8 - 8.13

8.4.1 Terraced houses

Tables 8.8 and 8.9 contain the optimum combined intervention results for the end and mid 19th century terraced houses. The base case total overheating was higher in the end-terraced house, where elderly occupants experienced between 168 degree hours (front north-facing) and 288 degree hours (front east-facing). The mid-terraced house overheating was greatest when the front was west-facing (202 degree hours for elderly occupants) and lowest for north-facing (99 degree hours for elderly occupants).

8.4.1.1 End-terraced house

The houses have solid walls, therefore cavity wall insulation is not an option and lower cost packages (below £5k) cannot include wall insulation interventions for the end-terraced house.

(a) Maximum overheating reduction

The best zero cost interventions were the same in each case and combined the window rules intervention with closing the curtains during the daytime. These two behavioural interventions had no effect on heating energy use, whilst reducing overheating to 99 degree hours (41% reduction) for elderly occupants and 74 degree hours (29% reduction) for family occupants when the front of the house (living room) was west-facing.

Overheating was reduced to between 8 and 14 degree hours for the low cost combined interventions, but the absence of wall insulation resulted in up to 14% greater space heating energy use, due to the loss of beneficial winter solar gains from the combined effects of external fixed shading, light walls and light roof.

The extra overheating reduction for medium cost interventions compared to low cost interventions was marginal. Although the increased budget would have allowed the addition of internal wall insulation, this could not be combined with other interventions within the budget to produce the lowest overheating, except for one case (front north-facing with family occupancy). In all other cases the solar control interventions resulted in greater heating energy use than the base case. Using the retrofit toolkit shows how adding insulation in combination with other interventions can reduce heating energy use, with a small compromise in overheating reduction. For example in the front south-facing case with elderly occupancy the optimum overheating reduction was 97% to 6 degree hours, but heating energy use increased by 9%. Using internal wall insulation, light roof, loft insulation, window rules, night ventilation and curtains, the overheating reduction was 96% (to 9 degree hours), but heating energy use was reduced by 47%. However, although still within the medium cost budget, this combination cost an extra £3.4k.

It was possible to completely eliminate overheating for all orientations and both occupancy profiles by implementing higher cost combined interventions, although it was found to be significantly more expensive to adapt east/west oriented houses than north/south oriented ones. For east/west houses it was necessary to use more expensive external wall insulation to eliminate overheating, whereas internal insulation could be used for the north/south orientations. The higher cost combined interventions for overheating reduction also reduced heating energy use by 41-43%.

(b) Maximum heating energy reduction

When selecting interventions for maximum heating energy use reduction, the low cost interventions were limited to the benefit from increasing the level of loft insulation, which reduced energy use by 2-3% compared to the base case. When loft insulation was combined with night ventilation, window rules and external shutters a reduction of 74% in overheating, to 44 degree hours, was achieved for the front west facing with elderly occupancy.

It was possible to improve heating energy performance with the medium cost interventions by adding internal wall insulation and reducing energy use by 48-53%. The cost of internal wall insulation meant that external shutters could not be included in this budget (£5-10k) and they were replaced by less effective internal blinds. The same combination of medium cost interventions (internal wall insulation, loft insulation, night ventilation, window rules and internal blinds) reduced overheating by 74-88%.

Overheating was reduced further (up to 96% reduction) by changing to external wall insulation, adding low e triple-glazing and changing the internal blinds back to external shutters. However, this cost an additional £9.6k and only resulted in a small extra heating energy use reduction due to the low e triple-glazing.

		Elderly occupancy profile					Family occupancy profile				
Orientation	Cost	Base DH	DH (%)	H (%)	Interventions (see key in Table 8.7)	£k	Base DH	DH (%)	H (%)	Interventions	£k
(a) Maximum overheating reduction at the lowest cost in each band											
Front	Zero	**168**	110 (-35)	0	WR+C	0	**116**	92 (-21)	0	WR+C	0
North	Low		8 (-95)	+11	LW+LR+NV+WR+FS+C	3.8		8 (-93)	+12	LW+LR+NV+WR+FS+C	3.8
	Med		6 (-96)	+11	LW+LR+NV+WR+FS+S	7.1		6 (-95)	-43	IW+LW+LR+WR+C	9.9
	High		0 (-100)	-41	IW+LW+LR+NV+WR+S	13.6		0 (-100)	-41	IW+LW+LR+NV+WR+FS+S	14.8
Front	Zero	**288**	207 (-28)	0	WR+C	0	**180**	148 (-18)	0	WR+C	0
East	Low		14 (-95)	+13	LW+LR+NV+WR+FS+C	4.8		14 (-92)	+14	LW+LR+NV+WR+FS+C	4.8
	Med		10 (-97)	+13	LW+LR+NV+WR+FS+S	8.0		11 (-94)	+14	LW+LR+NV+WR+FS+S	8.0
	High		0 (-100)	-41	EW+LW+LR+NV+WR+S	18.7		0 (-100)	-41	EW+LW+LR+NV+WR+FS+S	20.9
Front	Zero	**215**	129 (-40)	0	WR+C	0	**124**	92 (-26)	0	WR+C	0
South	Low		8 (-96)	+11	LW+LR+NV+WR+FS+C	4.4		8 (-94)	+11	LW+LR+NV+WR+FS+C	4.4
	Med		6 (-97)	+9	LW+LR+NV+WR+S	5.8		6 (-95)	+11	LW+LR+NV+WR+FS+S	7.7
	High		0 (-100)	-43	IW+LW+LR+NV+WR+S	13.6		0 (-100)	-43	IW+LW+LR+NV+WR+FS+S	15.5
Front	Zero	**169**	99 (-41)	0	WR+C	0	**104**	74 (-29)	0	WR+C	0
West	Low		8 (-95)	+8	LW+LR+NV+WR+FS+C	4.1		8 (-92)	+9	LW+LR+NV+WR+FS+C	4.1
	Med		5 (-97)	+8	LW+LR+NV+WR+FS+S	7.4		6 (-94)	+8	LW+LR+NV+WR+S	5.8
	High		0 (-100)	-41	EW+LW+LR+NV+WR+FS+C	17.0		0 (-100)	-43	EW+LW+LR+NV+WR+FS+B	18.6
(b) Optimum for space heating energy reduction with low overheating - zero cost always the same as (a)											
Front	Low	**168**	66 (-61)	-2	L+NV+WR+S	3.8	**116**	61 (-47)	-3	L+NV+WR+S	3.8
North	Med		23 (-86)	-48	IW+L+NV+WR+B	9.9		24 (-79)	-50	IW+L+NV+WR+B	9.9
	High		9 (-95)	-49	IW+L+NV+WR+LG+S	16.7		11 (-91)	-52	IW+L+NV+WR+LG+S	16.7
Front	Low	**288**	110 (-62)	-2	L+NV+WR+S	3.8	**180**	93 (-48)	-3	L+NV+WR+S	3.8
East	Med		51 (-82)	-48	IW+L+NV+WR+B	9.9		46 (-74)	-51	IW+L+NV+WR+B	9.9
	High		19 (-93)	-49	IW+L+NV+WR+LG+S	16.7		20 (-89)	-52	IW+L+NV+WR+LG+S	16.7
Front	Low	**215**	59 (-73)	-2	L+NV+WR+S	3.8	**124**	53 (-57)	-3	L+NV+WR+S	3.8
South	Med		25 (-88)	-49	IW+L+NV+WR+B	9.9		24 (-81)	-52	IW+L+NV+WR+B	9.9
	High		8 (-96)	-50	IW+L+NV+WR+LG+S	16.7		9 (-93)	-53	IW+L+NV+WR+LG+S	16.7
Front	Low	**169**	44 (-74)	-2	L+NV+WR+S	3.8	**104**	39 (-63)	-2	L+NV+WR+S	3.8
West	Med		32 (-81)	-48	IW+L+NV+WR+B	9.9		27 (-74)	-51	IW+L+NV+WR+B	9.9
	High		9 (-95)	-49	IW+L+NV+WR+LG+S	16.7		10 (-90)	-52	IW+L+NV+WR+LG+S	16.7

DH (%) = Total overheating degree hours % change from base case; H (%) = Heating energy use % change from base case

Table 8.8 – End terraced house combined interventions

		Elderly occupancy profile					Family occupancy profile				
Orientation	Cost	Base DH	DH (%)	H (%)	Interventions (see key in Table 8.7)	£k	Base DH	DH (%)	H (%)	Interventions	£k
(a) Maximum overheating reduction at the lowest cost in each band											
Front North	Zero	**99**	48 (-52)	0	WR+C	0	**66**	45 (-32)	0	WR+C	0
	Low		1 (-99)	+9	LW+LR+NV+WR+FS+B	4.9		2 (-97)	+10	LW+LR+NV+WR+FS+C	3.3
	Med		0 (-100)	-32	IW+LR+NV+WR+FS+C	7.2		0 (-100)	-34	IW+LW+LR+NV+WR+FS+C	8.0
	High		0 (-100)	-33	IW+LW+LR+NV+WR+S	10.0		0 (-100)	-35	IW+LW+LR+NV+WR+S	10.0
Front East	Zero	**195**	107 (-45)	0	WR+C	0	**105**	73 (-31)	0	WR+C	0
	Low		6 (-97)	+9	LW+LR+NV+WR+FS+C	3.6		6 (-94)	+10	LW+LR+NV+WR+FS+C	3.6
	Med		2 (-99)	-32	IW+LW+LR+NV+WR+FS+B	9.9		3 (-97)	+10	LW+LR+NV+WR+FS+C	6.9
	High		0 (-100)	-33	EW+LW+LR+NV+WR+S	13.1		0 (-100)	-34	EW+LW+LR+NV+WR+FS+S	14.7
Front South	Zero	**173**	77 (-56)	0	WR+C	0	**78**	47 (-40)	0	WR+C	0
	Low		2 (-99)	+10	LW+LR+NV+WR+FS+C	3.9		2 (-97)	+11	LW+LR+NV+WR+FS+C	3.9
	Med		0 (-100)	-32	IW+LW+LR+NV+WR+FS+C	8.6		0 (-100)	-34	IW+LW+LR+NV+WR+FS+C	8.6
	High		0 (-100)	-34	IW+LW+LR+NV+WR+S	10.0		0 (-100)	-37	IW+LW+LR+NV+WR+S	10.0
Front West	Zero	**202**	114 (-44)	0	WR+C	0	**116**	78 (-33)	0	WR+C	0
	Low		5 (-98)	+10	LW+LR+NV+WR+FS+C	4.3		5 (-96)	+10	LW+LR+NV+WR+FS+C	4.3
	Med		2 (-99)	+10	LW+LR+NV+WR+FS+S	7.5		2 (-98)	-34	IW+LW+LR+NV+WR+FS+C	8.9
	High		0 (-100)	-31	EW+LW+LR+NV+WR+FS+C	12.1		0 (-100)	-34	IW+LW+LR+NV+WR+FS+S	12.2
(b) Optimum for space heating energy reduction with low overheating - zero cost always the same as (a)											
Front North	Low	**99**	25 (-75)	-41	IW+L+WR+C	4.8	**66**	24 (-64)	-44	IW+L+WR+C	4.8
	Med		17 (-83)	-42	IW+L+WR+LG+C	9.9		17 (-74)	-45	IW+L+WR+LG+C	9.9
	High		3 (-97)	-42	IW+L+NV+WR+LG+S	13.6		4 (-94)	-45	IW+L+NV+WR+LG+S	13.6
Front East	Low	**195**	66 (-66)	-41	IW+L+WR+C	4.8	**105**	48 (-54)	-44	IW+L+WR+C	4.8
	Med		38 (-81)	-42	IW+L+WR+LG+C	9.9		33 (-69)	-46	IW+L+WR+LG+C	9.9
	High		8 (-96)	-42	IW+L+NV+WR+LG+S	13.6		8 (-92)	-46	IW+L+NV+WR+LG+S	13.6
Front South	Low	**173**	38 (-78)	-42	IW+L+WR+C	4.8	**78**	28 (-64)	-45	IW+L+WR+C	4.8
	Med		22 (-87)	-43	IW+L+WR+LG+C	9.9		20 (-74)	-46	IW+L+WR+LG+C	9.9
	High		3 (-98)	-43	IW+L+NV+WR+LG+S	13.6		3 (-96)	-46	IW+L+NV+WR+LG+S	13.6
Front West	Low	**202**	70 (-65)	-41	IW+L+WR+C	4.8	**116**	45 (-61)	-44	IW+L+WR+C	4.8
	Med		37 (-82)	-42	IW+L+WR+LG+C	9.9		30 (-74)	-45	IW+L+WR+LG+C	9.9
	High		7 (-97)	-42	IW+L+NV+WR+LG+S	13.6		7 (-94)	-45	IW+L+NV+WR+LG+S	13.6

DH (%) = Total overheating degree hours % change from base case; H (%) = Heating energy use % change from base case

Table 8.9 – Mid terraced house combined interventions

8.4.1.2 Mid-terraced house

(a) Maximum overheating reduction

The mid-terraced house did not have the second unglazed external walls to the living room and main bedroom which, without solar protection, absorbed significant solar radiation in the end-terraced house. The zero cost combination of window rules and curtains was more effective in the mid-terraced house, reducing overheating by up to 56% (to 77 degree hours) for elderly occupants when the living room was south-facing.

In common with the end-terraced house, the best low cost intervention combinations for overheating reduction included fixed solar control interventions without any insulation upgrades. These interventions increased heating energy use (by 9-11%), whilst reducing overheating to between 1 and 6 degree hours (up to 99% reduction).

The smaller external wall area of the mid-terraced house reduced the cost of fitting wall insulation compared to the end-terraced house. For north/south orientations it was possible to eliminate overheating using a medium cost package of interventions costing £7.2k - £8.6k, whilst also reducing heating energy use by 32-34%. For east/west orientations it was not possible to completely eliminate overheating with medium cost interventions, although it was reduced to 2 or 3 degree hours. When the front was west-facing with elderly occupancy and east-facing with family occupancy the least expensive medium cost interventions for maximum overheating reduction did not include wall insulation, which resulted in 10% greater heating energy use than the base case. Using the retrofit toolkit it can be shown that adding loft and internal wall insulation (at a cost of approx £4.8k) and replacing shutters (cost approx £3.3k) with curtains (free) would increase the retrofit cost for the west-facing elderly occupancy case to £9.9k (still within budget). However, this would reduce heating energy use by 36%, whilst still reducing overheating to 2 degree hours.

High cost combined interventions eliminated overheating in all cases and reduced heating energy use by 31-37%. The extra budget for north/south orientations allowed the replacement of curtains and external fixed shading with external shutters, which improved heating energy use by a further 1-3%. In common with the end-terraced house, the east/west orientations were the most expensive for which to eliminate overheating, although the cost to achieve this was £4.9-6.4k less than for the end-terraced house.

(b) Maximum heating energy reduction

The inclusion of internal wall insulation with extra loft insulation in the low cost interventions reduced heating energy use by up to 45%. The insulation interventions used £4.8k of the £5k budget, which ruled out any further costed interventions, but did allow the inclusion of window rules and curtains. The low cost interventions reduced overheating to between 25 and 70 degree hours for elderly occupants and 24-48 degree hours for family occupants, being most effective for the front south-facing orientation.

The medium cost band allowed the addition of low e triple-glazing to the low cost intervention package, reducing overheating to between 17 and 38 degree hours. The glazing upgrade also reduced heating energy use marginally, although at an extra estimated cost of £5.1k.

The high cost interventions did not reduce heating energy use any further, but allowed the replacement of curtains with external shutters and the addition of night ventilation, at an additional cost of £3.7k. This reduced overheating by up to 98% to between 3 and 8 degree hours.

8.4.2 Semi-detached house

Table 8.10 contains the optimum combined intervention results for the 1930s semi-detached house. The base case total overheating exposure ranged from 216-348 degree hours for elderly occupants and 114-183 degree hours for family occupants, with east/west orientations showing similar high levels of overheating.

(a) Maximum overheating reduction

The zero cost combined interventions of window rules and curtains reduced overheating by 26-42% and was most effective for the south-facing orientation.

The availability of cavity wall insulation allowed both overheating and space heating energy use to be reduced with a package of low cost interventions. For the south-facing orientation overheating was reduced by 99% to 4 degree hours for elderly occupants, with heating energy use reduced by 26%. The best overheating reduction for the east-facing orientation with low cost interventions (93% for elderly and 88% for family) was achieved through solar protection and ventilation interventions only and resulted in a 12% increase in heating energy use. However, using the toolkit shows that a different combination of interventions (cavity wall insulation, loft insulation, night ventilation, window rules, external fixed shading and curtains) still reduced overheating by 92% for elderly occupants and 86% for family occupants, whilst decreasing heating energy use by 26% and 32% respectively.

Medium cost combined interventions were able to reduce overheating by 95-99%, although heating energy use reduction was not as high as in the low cost interventions in some cases. This was due to the omission of the loft insulation intervention, which was not required to achieve the greatest overheating reduction. Taking as an example the case for elderly occupancy with the front south-facing, overheating reduction was unchanged at 99% (1 degree hour) when adding loft insulation to the package of interventions. This was a low cost intervention (approx. £150) and could be added within the medium cost budget.

Using high cost interventions (over £10k) overheating was eliminated in all cases for elderly occupancy and for the north/south orientations for family occupancy. The overheating for east/west orientations for family occupancy was reduced to 1 degree hour in each case. The cost to eliminate overheating for east/west orientations for elderly occupancy was significantly greater than for north/south orientations (£12.7k higher) due to the use of external wall insulation rather than cavity wall insulation, although the other benefit was a greater reduction in heating energy use.

The retrofit toolkit can be used to locate alternative high cost combined interventions. For example, for the west-facing case with elderly occupancy, if external wall insulation was replaced with loft and cavity wall insulation, the heating energy reduction changed from 38% to 31%, and overheating degree hours from zero to 1 at a cost saving of £11.3k. Alternatively, removing the low e triple-glazing, but keeping external wall insulation and adding loft insulation, improved the heating energy reduction to 40%, whilst still reducing overheating to 2 degree hours at a cost saving of £9.3k.

(b) Maximum heating energy reduction

Heating energy use was reduced by 33-36% for the low cost interventions by installing cavity wall insulation and extra loft insulation. The addition of external shutters and the window rules intervention reduced overheating by 82-91% for elderly occupants and 77-84% for family occupants.

Greater heating energy reductions (43-46%) were possible for the medium cost budget by fitting internal wall insulation in place of cavity wall insulation. However, this only left sufficient funds to fit internal blinds and use ventilation control interventions, therefore overheating reduction was worse than for low cost interventions.

		Elderly occupancy profile					Family occupancy profile				
Orientation	Cost	Base DH	DH (%)	H (%)	Interventions (see key in Table 8.7)	£k	Base DH	DH (%)	H (%)	Interventions	£k
(a) Maximum overheating reduction at the lowest cost in each band											
Front North	Zero	**216**	140 (-35)	0	WR+C	0	**114**	78 (-32)	0	WR+C	0
	Low		8 (-96)	-27	CW+LW+L+NV+WR+FS+C	4.8		9 (-92)	-27	CW+LW+L+NV+WR+FS+C	4.7
	Med		2 (-99)	-26	CW+LW+LR+NV+WR+S	7.3		3 (-97)	-26	CW+LW+LR+NV+WR+S	7.3
	High		0 (-100)	-23	CW+LW+LR+NV+WR+FS+LG+S	19.6		0 (-100)	-39	EW+LW+LR+NV+WR+LG+S	28.2
Front East	Zero	**348**	244 (-30)	0	WR+C	0	**183**	135 (-26)	0	WR+C	0
	Low		26 (-93)	+12	LW+LR+NV+WR+B	4.8		22 (-88)	+12	LW+LR+NV+WR+B	4.8
	Med		7 (-98)	-24	CW+LW+LR+NV+WR+S	7.3		8 (-96)	-20	CW+LW+LR+NV+WR+FS+C	7.0
	High		0 (-100)	-35	EW+LW+LR+NV+WR+FS+LG+S	32.3		1 (-99)	-35	EW+LW+LR+WR+FS+LG+S	31.9
Front South	Zero	**270**	157 (-42)	0	WR+C	0	**139**	89 (-36)	0	WR+C	0
	Low		4 (-99)	-26	CW+LW+L+NV+WR+FS+C	4.3		5 (-96)	-26	CW+LW+L+NV+WR+FS+C	4.3
	Med		1 (-99)	-21	CW+LW+LR+NV+WR+FS+S	9.7		1 (-99)	-20	CW+LW+LR+NV+WR+FS+S	9.7
	High		0 (-100)	-24	CW+LW+LR+NV+WR+FS+LG+S	19.2		0 (-100)	-23	CW+LW+LR+NV+WR+FS+LG+S	19.2
Front West	Zero	**307**	206 (-33)	0	WR+C	0	**174**	124 (-29)	0	WR+C	0
	Low		26 (-92)	-32	CW+L+NV+WR+FS+C	4.5		23 (-87)	+9	LW+WR+FS+C	4.9
	Med		8 (-97)	-27	CW+LW+LR+NV+WR+S	7.3		9 (-95)	-26	CW+LW+LR+NV+WR+S	7.3
	High		0 (-100)	-38	EW+LW+LR+NV+WR+FS+LG+S	32.0		1 (-99)	-38	EW+LW+LR+NV+WR+FS+LG+S	32.0
(b) Optimum for space heating energy reduction with low overheating - zero cost always the same as (a)											
Front North	Low	**216**	21 (-90)	-36	CW+L+WR+S	4.9	**114**	18 (-84)	-35	CW+L+WR+S	4.9
	Med		36 (-83)	-46	IW+L+NV+WR+B	9.7		30 (-74)	-45	IW+L+NV+WR+B	9.7
	High		2 (-99)	-47	EW+L+NV+WR+LG+S	27.1		3 (-97)	-47	EW+L+NV+WR+LG+S	27.1
Front East	Low	**348**	61 (-83)	-34	CW+L+WR+S	4.9	**183**	42 (-77)	-33	CW+L+WR+S	4.9
	Med		80 (-77)	-44	IW+L+NV+WR+B	9.7		57 (-69)	-43	IW+L+NV+WR+B	9.7
	High		13 (-96)	-46	IW+L+NV+WR+LG+S	21.5		9 (-95)	-46	EW+L+NV+WR+LG+S	27.1
Front South	Low	**270**	24 (-91)	-34	CW+L+WR+S	4.9	**139**	22 (-84)	-34	CW+L+WR+S	4.9
	Med		36 (-87)	-44	IW+L+NV+WR+B	9.7		32 (-77)	-44	IW+L+NV+WR+B	9.7
	High		6 (-98)	-47	IW + L + NV + WR + LG + S	21.5		4 (-97)	-46	EW+L+NV+WR+LG+S	27.1
Front West	Low	**307**	55 (-82)	-35	CW+L+WR+S	4.9	**174**	40 (-77)	-34	CW+L+WR+S	4.9
	Med		87 (-72)	-45	IW+L+NV+WR+B	9.7		63 (-64)	-44	IW+L+NV+WR+B	9.7
	High		13 (-96)	-47	IW+L+NV+WR+LG+S	21.5		8 (-95)	-47	EW+L+NV+WR+LG+S	27.1

DH = Total overheating degree hours (% change from base case); %H = Heating energy use % change from base case

Table 8.10 – Semi-detached house combined interventions

The high cost interventions added low e triple-glazing and replaced the internal blinds with external shutters, producing a marginal improvement in heating energy use, but reducing overheating to between 2 and 13 degree hours. For both occupancy profiles, when the front was north-facing the heating energy reduction was 47% and overheating was reduced to 2 degree hours (elderly) and 3 degree hours (family) at a cost of £27.1k. However, excluding the low e triple-glazing from the interventions had a small effect on the results, increasing overheating by 3 degree hours and heating energy use by 1% compared to the optimum results, but at a significantly lower cost of £17.7k.

8.4.3 Flats

The top floor flat simulation results were presented in Chapter 7. Tables 8.11 and 8.12 contain the optimum combined intervention results for the ground and first floor 1960s flats.

8.4.3.1 Ground floor flat

The ground floor flat base case total overheating was low compared to the upper floor flats. Elderly occupants experienced between 106 degree hours (rooms north-facing) and 290 degree hours (rooms west-facing) and family occupants 55-193 degree hours.

(a) Maximum overheating reduction

The zero cost behavioural interventions (window rules and curtains) reduced overheating by 36-66% and was most effective when the front of the block faced south (living room and main bedroom north-facing), where overheating was reduced to 36 degree hours for elderly occupants and 21 degree hours for family occupants.

It was the easiest dwelling type to adapt for overheating reduction and in all cases overheating could be eliminated for less than £5k. However, it should be noted that in many cases a whole block of flats would be retrofitted at the same time. The best performing interventions vary and depend on the position of the flat in the block (see Sections 7.3 and 8.4.3.2). Internal interventions can be applied to single flats, but external modifications would usually be applied uniformly and affect the whole building.

When the front of the block faced south (living room and main bedroom north-facing) overheating in the ground floor flat could be eliminated for £0.8-1.2k, with a 30% reduction in heating energy use resulting from the addition of cavity wall insulation.

There was no advantage for overheating reduction in spending more than the low cost budget and increasing to the medium budget actually increased heating energy use through the addition of further solar control interventions. With the higher cost budget it was possible to marginally reduce the heating energy use through the addition of low e triple-glazing, although at an additional cost of £6.1k.

(b) Maximum heating energy reduction

Internal wall insulation, curtains and the two ventilation control strategies cost an estimated £5k for the ground floor flat and reduced heating energy use by 36-42% and overheating by 76-99%.

The medium cost interventions added either low e triple-glazing or the upgraded roof, depending on orientation, neither of which had a significant effect on heating energy use (less than 1%), although overheating was reduced to between zero and 39 degree hours.

High cost interventions allowed the addition of both low e triple-glazing and upgrading the flat roof. These marginally improved the heating energy use further and overheating was eliminated in all cases.

		Elderly occupancy profile					Family occupancy profile				
Orientation	Cost	Base DH	DH (%)	H (%)	Interventions (see key in Table 8.7)	£k	Base DH	DH (%)	H (%)	Interventions	£k
(a) Maximum overheating reduction at the lowest cost in each band											
Front North	Zero	**261**	132 (-49)	0	WR+C	0	**138**	60 (-57)	0	WR+C	0
	Low		0 (-100)	-25	CW+NV+WR+FS+C	2.4		0 (-100)	-28	CW+LW+NV+WR+B	2.4
	Med		0 (-100)	-22	CW+LW+UR+WR+FS+C	5.2		0 (-100)	-18	CW+LW+UR+WR+FS	5.1
	High		0 (-100)	-31	IW+LW+LR+UR+NV+WR+FS	10.0		0 (-100)	-27	IW+LW+LR+UR+NV+FS+C	10.0
Front East	Zero	**290**	181 (-38)	0	WR+C	0	**193**	123 (-36)	0	WR+C	0
	Low		0 (-100)	-28	CW+LW+NV+WR+S	4.4		0 (-100)	-25	CW+LW+NV+WR+S	4.4
	Med		0 (-100)	-21	CW+LW+LR+NV+WR+FS+C	5.3		0 (-100)	-18	CW+LW+LR+NV+WR+FS+C	5.3
	High		0 (-100)	-34	CW+LR+NV+WR+LG+S	10.1		0 (-100)	-30	CW+LR+NV+WR+LG+S	10.1
Front South	Zero	**106**	36 (-66)	0	WR+C	0	**55**	21 (-62)	0	WR+C	0
	Low		0 (-100)	-30	CW+LW+NV+WR+C	1.2		0 (-100)	-30	CW+LR+NV+WR+C	0.8
	Med		0 (-100)	-27	CW+WR+FS+S	5.1		0 (-100)	-25	CW+FS+S	5.1
	High		0 (-100)	-27	CW+LW+WR+FS+LG+B	10.0		0 (-100)	-23	CW+LW+FS+LG+B	10.0
Front West	Zero	**251**	128 (-49)	0	WR+C	0	**134**	67 (-50)	0	WR+C	0
	Low		0 (-100)	-31	CW+LW+NV+WR+S	4.4		0 (-100)	-28	CW+LW+NV+WR+S	4.4
	Med		0 (-100)	-23	CW+LW+LR+NV+WR+FS+C	5.3		0 (-100)	-20	CW+LW+LR+NV+WR+FS+C	5.3
	High		0 (-100)	-35	CW+LR+NV+WR+LG+S	10.1		0 (-100)	-31	CW+LR+NV+LG+S	10.1
(b) Optimum for space heating energy reduction with low overheating - zero cost always the same as (a)											
Front North	Low	**261**	38 (-85)	-42	IW+NV+WR+C	5.0	**138**	5 (-96)	-39	IW+NV+WR+C	5.0
	Med		10 (-96)	-42	IW+UR+NV+WR+B	8.4		2 (-99)	-39	IW+UR+NV+WR+B	8.4
	High		0 (-100)	-43	IW+UR+WR+LG+S	16.2		0 (-100)	-40	EW+UR+WR+S	14.0
Front East	Low	**290**	71 (-76)	-39	IW+NV+WR+C	5.0	**193**	44 (-77)	-36	IW+NV+WR+C	5.0
	Med		39 (-87)	-39	IW+UR+NV+WR+B	8.4		25 (-87)	-36	IW+UR+NV+WR+B	8.4
	High		0 (-100)	-42	IW+UR+NV+WR+LG+S	16.4		0 (-100)	-38	IW+UR+NV+WR+LG+S	16.4
Front South	Low	**106**	1 (-99)	-41	IW+NV+WR+C	5.0	**55**	1 (-98)	-37	IW+NV+WR+C	5.0
	Med		1 (-99)	-41	IW+UR+NV+WR+B	8.4		0 (-100)	-37	IW+UR+NV+WR+B	8.4
	High		0 (-100)	-43	IW+UR+WR+LG+S	16.2		0 (-100)	-39	IW+UR+NV+WR+LG	13.3
Front West	Low	**251**	38 (-85)	-40	IW+NV+WR+C	5.0	**134**	14 (-90)	-37	IW+NV+WR+C	5.0
	Med		20 (-92)	-40	IW+UR+NV+WR+B	8.4		7 (-95)	-37	IW+UR+NV+WR+B	8.4
	High		0 (-100)	-43	IW+UR+NV+WR+LG+S	16.4		0 (-100)	-39	IW+UR+NV+WR+LG+S	16.4

DH (%) = Total overheating degree hours % change from base case; H (%) = Heating energy use % change from base case

Table 8.11 – Ground floor flat combined interventions

		Elderly occupancy profile					Family occupancy profile				
Orientation	Cost	Base DH	DH (%)	H (%)	Interventions (see key in Table 8.7)	£k	Base DH	DH (%)	H (%)	Interventions	£k
(a) Maximum overheating reduction at the lowest cost in each band											
Front North	Zero	**665**	365 (-45)	0	NV+WR+C	0	**391**	218 (-44)	0	NV+WR+C	0
	Low		18 (-97)	-28	CW+LW+LR+NV+WR+FS+B	4.6		11 (-97)	-25	CW+LW+LR+NV+WR+FS+B	4.6
	Med		7 (-99)	-28	CW+LW+LR+NV+WR+FS+S	6.6		4 (-99)	-25	CW+LW+LR+NV+WR+FS+S	6.6
	High		1 (-100)	-45	EW+LW+LR+NV+WR+FS+LG+S	20.5		1 (-100)	-40	EW+LW+LR+NV+WR+FS+LG+S	20.5
Front East	Zero	**738**	435 (-41)	0	NV+WR+C	0	**467**	295 (-37)	0	NV+WR+C	0
	Low		74 (-90)	+13	LW+LR+NV+WR+S	4.4		56 (-88)	+13	LW+LR+NV+WR+S	4.4
	Med		45 (-94)	+21	LW+LR+NV+WR+FS+S	8.1		31 (-93)	-24	CW+LW+LR+NV+WR+FS+S	8.3
	High		9 (-99)	-45	EW+LW+LR+NV+WR+FS+LG+S	22.2		7 (-99)	-40	EW+LW+LR+NV+WR+FS+LG+S	22.2
Front South	Zero	**400**	188 (-53)	0	NV+WR+C	0	**232**	121 (-48)	0	NV+WR+C	0
	Low		11 (-97)	-36	CW+LW+LR+NV+WR+S	4.6		7 (-97)	-33	CW+LW+LR+NV+WR+S	4.6
	Med		6 (-99)	-30	CW+LW+LR+NV+WR+FS+S	6.3		4 (-98)	-27	CW+LW+LR+NV+WR+FS+S	6.3
	High		1 (-100)	-47	EW+LW+LR+NV+WR+FS+LG+S	20.2		1 (-100)	-46	EW+LW+LR+NV+WR+LG+S	18.5
Front West	Zero	**684**	372 (-46)	0	NV+WR+C	0	**385**	221 (-43)	0	NV+WR+C	0
	Low		58 (-92)	+9	LW+LR+NV+WR+S	4.4		38 (-90)	+10	LW+LR+NV+WR+S	4.4
	Med		33 (-95)	+18	LW+LR+NV+WR+FS+S	8.1		22 (-94)	+18	LW+LR+NV+WR+FS+S	8.1
	High		6 (-99)	-46	EW+LW+LR+NV+WR+FS+LG+S	22.2		4 (-99)	-42	EW+LW+LR+NV+WR+FS+LG+S	22.2
(b) Optimum for space heating energy reduction with low overheating - zero cost always the same as (a)											
Front North	Low	**665**	310 (-53)	-51	IW+NV+WR+C	4.8	**391**	165 (-58)	-48	IW+NV+WR+C	4.8
	Med		236 (-65)	-55	IW+UR+NV+WR+B	8.2		130 (-67)	-53	IW+UR+NV+WR+B	8.2
	High		19 (-97)	-59	EW+UR+NV+WR+LG+S	20.1		14 (-96)	-56	EW+UR+NV+WR+LG+S	20.1
Front East	Low	**738**	400 (-46)	-47	IW+NV+WR+C	4.8	**467**	255 (-45)	-44	IW+NV+WR+C	4.8
	Med		331 (-55)	-51	IW+UR+NV+WR+B	8.2		218 (-53)	-48	IW+UR+NV+WR+B	8.2
	High		61 (-92)	-57	EW+UR+NV+WR+LG+S	20.1		42 (-91)	-54	EW+UR+NV+WR+LG+S	20.1
Front South	Low	**400**	168 (-58)	-50	IW+NV+WR+C	4.8	**232**	96 (-59)	-46	IW+NV+WR+C	4.8
	Med		125 (-69)	-54	IW+UR+NV+WR+B	8.2		74 (-68)	-51	IW+UR+NV+WR+B	8.2
	High		10 (-98)	-59	EW+UR+NV+WR+LG+S	20.1		6 (-97)	-55	EW+UR+NV+WR+LG+S	20.1
Front West	Low	**684**	381 (-44)	-48	IW+NV+WR+C	4.8	**385**	217 (-44)	-45	IW+NV+WR+C	4.8
	Med		313 (-54)	-52	IW+UR+NV+WR+B	8.2		182 (-53)	-50	IW+UR+NV+WR+B	8.2
	High		44 (-94)	-58	EW+UR+NV+WR+LG+S	20.1		28 (-93)	-55	EW+UR+NV+WR+LG+S	20.1

DH (%) = Total overheating degree hours % change from base case; H (%) = Heating energy use % change from base case

Table 8.12 – First floor flat combined interventions

8.4.3.2 First floor flat

The total overheating experienced in the first floor flat, though lower than in the top floor flat, was still high at between 400 degree hours (rooms north-facing) and 738 degree hours (rooms west-facing) for elderly occupants and 236-472 degree hours for family occupants.

(a) Maximum overheating reduction

It was assumed that windows could be left open at night in flats above the ground floor without security upgrade costs. The zero cost interventions therefore included night ventilation in addition to window rules and curtains and together reduced overheating by 37-53%. However, the base case overheating in each case was very high and elderly occupants still experienced between 188 and 435 degree hours over the threshold temperatures for the heat wave period.

Some of the low and medium cost combined interventions for maximum overheating reduction resulted in greater heating energy use due to solar control interventions without insulation upgrades. For the front east orientation with elderly occupancy, light walls, light roof, night ventilation, window rules and shutters reduced overheating by 90% to 74 degree hours, but heating energy use increased by 13% (at a cost of £4.4k). Using the toolkit an alternative retrofit package can be selected with similar overheating performance but with lower heating energy use. By changing the light roof intervention (which only had a small effect for flats other than the top floor) for cavity wall insulation, overheating would be reduced by 87% (to 96 degree hours), but heating energy use would be reduced by 35% at a similar cost (£4.2k).

It was not always possible to eliminate overheating at any cost in the first floor flat. To achieve maximum overheating reduction the cost varied between £18.5k and £22.2k, depending on orientation and occupancy, with east/west orientations being the most expensive to adapt. This compares to an estimated cost of £0.8k-4.4k to eliminate overheating in the ground floor flat.

(b) Maximum heating energy reduction

The first floor flat does not have heat losses through the floor or ceiling due to occupied spaces above and below, resulting in the external walls and windows being the only heat loss surfaces. The low cost intervention package, in each case consisting of internal wall insulation, night ventilation, window rules and curtains, reduced heating energy use by 44-51%, but overheating remained high at 168-400 degree hours for elderly occupants and 96-255 degree hours for family occupants.

The medium cost interventions added the upgraded roof and replaced curtains with internal blinds, which reduced heating energy use by a further 4-5%. Overheating was reduced to 125-331 degree hours for elderly occupants and 74-218 degree hours for family occupants.

The same high cost interventions, consisting of external wall insulation, upgraded roof, night ventilation, window rules, low e triple-glazing and shutters, was found to be most effective in each case, reducing heating energy use by up to 59%. The benefit of using external rather than internal wall insulation, combined with shutters and low e triple-glazing, reduced overheating significantly compared to the medium cost interventions. Overheating for the worst case orientation (front east-facing, living room and main bedroom west-facing) was reduced by 92% to 61 degree hours for elderly occupants and to 42 degree hours (91% reduction) for family occupants.

8.4.4 Detached house

The base case overheating was very high for the modern detached house and comparable to the first and top floor flats, at 464-721 degree hours for elderly occupants and 229-339 degree hours for family occupants. Table 8.13 contains the optimum combined intervention results for the detached house.

(a) Maximum overheating reduction

The zero cost combined interventions of window rules and curtains reduced overheating by 23-31%, but it remained very high at 321-544 degree hours for elderly occupants and 167-257 degree hours for the family.

The absence of any insulation interventions in all of the low, medium and high cost combined interventions for maximum overheating reduction resulted in greater heating energy use (up to 27% extra) due to the combination of solar protection measures.

It was not possible to eliminate overheating at any cost, although the high cost interventions reduced overheating by up to 99% to 4 degree hours for north and south-facing orientations with elderly occupancy, although at a cost of £25.4-26k.

(b) Maximum heating energy reduction

The detached house was already well insulated and there was no scope to improve space heating energy use within the selected range of interventions. Although low e triple-glazing had a lower U-value than the default low e double-glazing, the low SHGC of the triple-glazing reduced beneficial solar heat gains during the heating seasons.

The low and medium cost interventions combined the two ventilation interventions with either internal blinds or external shutters to avoid increasing heating energy use, which remained unchanged from the base case. Overheating for the low cost interventions using internal blinds remained high at 121-261 degree hours for elderly occupants and 90-159 degree hours for family occupants. The medium cost package

		Elderly occupancy profile					Family occupancy profile				
Orientation	Cost	Base DH	DH (%)	H (%)	Interventions (see key in Table 8.7)	£k	Base DH	DH (%)	H (%)	Interventions	£k
(a) Maximum overheating reduction at the lowest cost in each band											
Front North	Zero	**624**	440 (-30)	0	WR+C	0	**264**	190 (-28)	0	WR+C	0
	Low		74 (-88)	+9	LR+NV+WR+FS+C	5.0		54 (-80)	+9	LR+NV+WR+FS+C	5.0
	Med		21 (-97)	+5	LW+NV+WR+S	8.4		27 (-90)	+6	LW+NV+WR+S	8.4
	High		4 (-99)	+24	LW+LR+NV+WR+FS+LG+S	26.0		9 (-97)	+27	LW+LR+NV+WR+FS+LG+S	26.0
Front East	Zero	**719**	540 (-25)	0	WR+C	0	**339**	257 (-24)	0	WR+C	0
	Low		222 (-69)	+6	LW+LR+NV+WR+C	4.3		131 (-61)	+6	LW+LR+NV+WR+C	4.3
	Med		76 (-89)	+5	LW+NV+WR+S	8.4		69 (-80)	+5	LW+NV+WR+S	8.4
	High		13 (-98)	+21	LW+LR+NV+WR+FS+LG+S	28.6		21 (-94)	+21	LW+LR+NV+WR+FS+LG+S	28.6
Front South	Zero	**464**	321 (-31)	0	WR+C	0	**229**	167 (-27)	0	WR+C	0
	Low		59 (-87)	+7	LR+NV+WR+FS+C	4.4		53 (-77)	+7	LR+NV+WR+FS+C	4.4
	Med		19 (-96)	+5	LW+NV+WR+S	8.4		26 (-89)	+6	LW+NV+WR+S	8.4
	High		4 (-99)	+22	LW+LR+NV+WR+FS+LG+S	25.4		10 (-96)	+22	LW+LR+NV+WR+FS+LG+S	25.4
Front West	Zero	**721**	544 (-25)	0	WR+C	0	**321**	246 (-23)	0	WR+C	0
	Low		203 (-72)	+6	LW+LR+NV+WR+C	4.3		117 (-64)	+6	LW+LR+NV+WR+C	4.3
	Med		68 (-91)	+5	LW+NV+WR+S	8.4		58 (-82)	+5	LW+NV+WR+S	8.4
	High		12 (-98)	+21	LW+LR+NV+WR+FS+LG+S	28.4		19 (-94)	+21	LW+LR+NV+WR+FS+LG+S	28.4
(b) Optimum for space heating energy reduction with low overheating - zero cost always the same as (a)											
Front North	Low	**624**	189 (-70)	0	NV+WR+B	3.0	**264**	103 (-61)	0	NV+WR+B	3.0
	Med		53 (-92)	0	NV+WR+S	6.1		48 (-82)	0	NV+WR+S	6.1
	High		13 (-98)	+6	LW+LR+NV+WR+S	10.0		19 (93)	+7	LW+LR+NV+WR+S	10.0
Front East	Low	**719**	261 (-64)	0	NV+WR+B	3.0	**339**	159 (-53)	0	NV+WR+B	3.0
	Med		124 (-83)	0	NV+WR+S	6.1		99 (-71)	0	NV+WR+S	6.1
	High		59 (92)	+6	LW+LR+NV+WR+S	10.0		58 (83)	+6	LW+LR+NV+WR+S	10.0
Front South	Low	**464**	121 (-74)	0	NV+WR+B	3.0	**229**	90 (-61)	0	NV+WR+B	3.0
	Med		48 (-90)	0	NV+WR+S	6.1		49 (-79)	0	NV+WR+S	6.1
	High		12 (97)	+7	LW+LR+NV+WR+S	10.0		20 (91)	+7	LW+LR+NV+WR+S	10.0
Front West	Low	**721**	248 (-66)	0	NV+WR+B	3.0	**321**	147 (-54)	0	NV+WR+B	3.0
	Med		116 (-83)	0	NV+WR+S	6.1		88 (-73)	0	NV+WR+S	6.1
	High		52 (93)	+6	LW+LR+NV+WR+S	10.0		49 (85)	+6	LW+LR+NV+WR+S	10.0

DH (%) = Total overheating degree hours % change from base case; H (%) = Heating energy use % change from base case

Table 8.13 – Detached house combined interventions

using shutters performed significantly better, reducing overheating to 53-124 degree hours (elderly) and 48-99 degree hours (family).

It was not possible to improve upon the performance of the medium cost interventions without increasing heating energy use. The smallest increase (6-7%) was with the addition of the light roof and light walls interventions to the medium cost package. This reduced overheating to between 12 and 59 degree hours for family occupants and between 19 and 58 degree hours for family occupants at a total cost of £10k.

8.5 Summary

This chapter presented the simulation results for single and combined interventions for all the dwelling types, with the exception of the top floor flat, which was presented in Chapter 7. The costs and effect on space heating energy use of the interventions were also discussed for the two occupancy profiles and four orientations.

External shutters were identified as the most effective single intervention in most cases, with the exception of the terraced houses with solid brick walls, where light walls (solar reflective coating) was the most effective intervention.

Combined intervention results were presented for maximum overheating reduction and greatest heating energy use reduction for each dwelling type. The retrofit toolkit was used to provide alternative combined interventions to optimise overheating and energy use reductions at each cost band.

The next chapter will discuss the results from this and the previous two chapters and compare the retrofit options for the different cases.

Chapter 9

Discussion

9.1 Foreword

Chapters 6,7 and 8 presented the simulation results for the base case dwellings and for the addition of single and combined interventions for each case. This chapter discusses the results and compares the effect that interventions have on different dwelling types, including the effects of orientation and occupancy profiles on the results. The energy use and cost implications of different retrofit packages is also discussed.

It is suggested that the retrofit toolkit (Appendix B) is used to view the results discussed in this chapter. For a full description of the interventions see Chapter 4.

9.2 Base case dwelling overheating

CIBSE recommend that threshold temperatures of 28 °C for living rooms and 26 °C for bedrooms should not be exceeded for more than 1% of occupied hours (CIBSE, 2006). The shortcomings of this simple threshold approach were discussed in Chapters 2 and 5. To better represent the severity of overheating exposure overheating was quantified in terms of degree hours over the CIBSE threshold temperatures. In some cases it was possible to eliminate overheating with a limited range of interventions, but in other cases overheating could not be eliminated using the full range of interventions.

9.2.1 Effect of dwelling type

Seven dwellings, using four different simulation models, were chosen to represent a cross section of housing types and construction methods found in London and South East England (Chapter 3), which included 19th century end and mid-terraced houses; a 1930s semi-detached house; 1960s ground, first and top floor flats and a modern detached house.

The base case overheating varied significantly between the dwelling types, as discussed in Chapter 6. For elderly occupants the lowest base case overheating for total occupied periods (time spent in the living room and main bedroom combined) was 99 degree hours over the CIBSE comfort threshold temperatures in the mid-terraced house with north facing living room and south facing main bedroom windows. In the worst case dwelling, overheating exposure was 897 degree hours in the top floor flat with west facing living room and main bedroom windows. An 88% reduction in overheating in this case would therefore still result in greater overheating exposure than the lowest overheating mid-terraced house.

Two categories (Tiers) of dwelling types were identified for their vulnerability to overheating. The lowest overheating (Tier 1) dwellings comprised the two terraced houses and the ground floor flat, with slightly higher levels of overheating in the semi-detached house. Tier 2 dwellings, which included the mid and top floor flats and the detached house, experienced significantly higher overheating - up to 6.5 times greater when comparing the same orientations and occupancy profiles.

9.2.2 Effect of dwelling orientation and occupancy

Each dwelling type and occupancy profile was modelled with the front of the building facing north, south, east and west. Two occupancy profiles were modelled, the family profile assumed adults and school age children, who were all out of the dwellings during the daytime. The elderly profile, which could also cover infirm or housebound residents, assumed occupancy of the dwellings all the time and in particular daytime occupancy of the living room.

It was not straightforward comparing the effect of orientation across dwelling types, because in some cases the living room and main bedroom were on the same side of the building and in others on opposite sides. However, it is clear that dwelling orientation had a significant effect on overheating exposure. Considering the effect on individual rooms, the lowest overheating for both living rooms and main bedrooms occurred when they had north facing windows and in most cases the greatest overheating was recorded when the windows were west or east-facing. For example, overheating was 6 times higher for the mid-terraced living room with family occupancy when the windows faced west rather than north.

East-facing living room orientations were more problematic for daytime occupied dwellings (elderly occupants), where morning solar heat gains through the glazing increased overheating. West-facing living rooms increased overheating for family occupants, arriving home in the afternoon, although other factors such as south-facing solid walls (for example in the end-terraced house) could result in a variation of this general pattern.

Elderly occupants experienced typically double the total overheating exposure of the family occupants. The smallest difference (1.4 times the overheating exposure) occurred in the end-terraced house where the front was north-facing. In this case the living room was north-facing and did not overheat as much as other orientations during the daytime. The greatest difference occurred in the detached house, where overheating for elderly occupants was 2.4 times that for family occupants when the living room faced south. In this case the large glazed area of the patio doors resulted in significant solar heat gains throughout the daytime for the elderly occupants.

Although bedroom occupied periods were similar for both profiles, the elderly occupants experienced up to 1.2 times the bedroom overheating exposure of the family occupants due to increased dwelling temperatures through the day resulting in higher bedroom temperatures at bedtime (see Figure 6.5 in Chapter 6).

9.3 Effect of interventions on overheating and on heating energy use

The range of available interventions varied between dwelling types. The modern detached house assumed construction to 2006 Building Regulations and had a well insulated roof and walls, therefore loft and wall insulation interventions were not considered. The terraced houses had solid external walls, limiting the choice of wall insulation to external or internal. The flats and the semi-detached house had uninsulated cavity walls and, through the inclusion of cavity wall insulation, had the largest selection of possible interventions.

Some of the interventions had no effect on annual space heating energy use because they could be used selectively when required during hot weather. These included the two ventilation strategies (window rules and night ventilation) and the three window solar control interventions (external shutters, internal blinds and curtains). The remaining interventions affected heating energy use to varying degrees, depending on dwelling type, orientation and occupancy profile. The effect of single interventions on heating energy use were presented in Table 7.2 (Chapter 7) and Tables 8.1-8.4 (Chapter 8).

9.3.1 Effect of single interventions

External shutters

In all cases the addition of external shutters was very effective for reducing overheating. With the exception of 19th century terraced houses, external shutters was the single most effective intervention when considering total overheating reduction[1], typically reducing overheating by 50-60%. In the case of the ground floor flat with family occupancy and south-facing living room and main bedroom windows, fitting shutters reduced overheating by 81%.

In the case of the terraced houses, external shutters were still effective and were the highest ranked intervention for south and west-facing mid-terraced houses with elderly (daytime) occupancy. In other terraced house cases the light walls intervention was most effective (see the following section). The smallest benefit was seen in the end-terraced house with the front north-facing, where external shutters reduced total overheating by 23-25%.

Light walls

The solid walls of the terraced houses provided effective inward transmission of solar heat gains and for all terraced house variants, other than south and west-facing mid-terraced houses with elderly occupancy, painting the external walls with a high performance solar reflective coating (light walls) was the most effective single intervention.

The light walls intervention was also highly ranked for the semi-detached house and the flats, both of which had uninsulated cavity walls. For the main bedrooms, which were not occupied during the daytime, light walls was often the most effective intervention. In the case of the top floor flat, it was the best performing single

[1]In the case of the semi-detached house with family occupancy, external shutters was the equal highest ranked intervention with external fixed shading (south-facing) and light walls (east-facing).

intervention for most situations and it was only the case with east-facing living room and main bedroom windows and the family occupancy profile where external shutters outperformed light walls for main bedroom overheating reduction. It was a much less effective intervention for the modern detached house, which had highly insulated external walls.

Solar reflective coating the external walls produced similar increases in heating energy use (5-11%) for the flats, semi-detached house and end-terraced house, with the largest increases occurring when the unglazed end wall was south-facing in each case. The smaller wall area of mid-terraced house reduced the increase to between 4 and 5%. The detached house had a large external wall area, exposed on four sides, but the high level of wall insulation reduced the impact of the solar coating on energy use, which was limited to increases of 5-6%.

Light roof

The mid-terraced house bedrooms gained the greatest benefit from coating the roof with a solar reflective paint. Unlike the end-terraced house the roof surfaces were the only heat gain/heat loss surfaces for the loft space. For north and south-facing mid-terraced main bedrooms, where one slope of the roof faced south, it was the most effective single intervention, reducing overheating by up to 45%. For other dwellings it was a mid ranked intervention, with the exception of the modern detached house, where the benefit was much lower due to the well-insulated loft space.

The light roof intervention had a much smaller effect on living rooms, except for the top floor flat where the poorly insulated flat roof was directly above all the rooms. In this case overheating was reduced by up to 30%. For obvious reasons it had little effect on overheating in the ground and mid-floor flats.

Applying a solar reflecting coating to the roof had the greatest effect on heating energy use for the top floor flat. The poorly insulated flat roof was directly above all of the rooms and the coating reduced winter solar heat gains, increasing heating energy use by 6-7%. The effect was reduced for the mid floor flat (up to 3% increase) and for the ground floor flat the light roof intervention had virtually no effect on heating energy. The pitched roof construction combined with some loft insulation in the houses resulted in smaller increases in heating energy use of 1-3%. The smallest increases were observed in the detached house, which had a higher level of loft insulation in the base case.

Window rules

For the mid-terraced living room with north-facing windows there was little solar heat gain, either through walls or windows, and also little insulation to retain heat gains inside the room. In this case window rules (preventing windows opening if the outside air temperature is higher than inside) produced the greatest overheating reduction. In contrast, for the detached house and the first and top floor flats, window rules had very little effect. This was due to the high internal temperatures during the hottest parts of the day, which resulted in little opportunity to implement the intervention (see Figure 8.16 in Chapter 8). This demonstrates that if overheating adaptation is not considered during retrofit, the benefit of some zero cost interventions may be lost.

Night ventilation

Bedroom windows were opened at night by default when room operative temperatures exceeded 22 °C. However, the windows in unoccupied rooms were assumed to be closed (mostly for security reasons). The night ventilation intervention allowed ventilation by outside air to the unoccupied rooms at night during the heat wave period, cooling the building fabric overnight. It was an effective middle ranking intervention in all cases, but was most effective in percentage reduction terms for north-facing rooms, which had lower daytime solar heat gains. The greatest percentage total overheating reduction (up to 47%) was achieved in the ground floor flat, with the top floor flat recording the lowest reduction (up to 19%). In the case of the top floor flat high solar heat gains through the flat roof rapidly warmed the living space during the daytime. The largest absolute reduction in degree hours was observed in the west-facing detached house living room with elderly occupancy, where overheating was reduced from 509 to 323 degree hours, a drop of 186 degree hours (37%). The west-facing windows were not exposed to significant solar radiation until the afternoon, allowing the night cooling benefit to persist through the daytime.

Elderly residents who occupied the dwellings during the daytime benefitted slightly more than family occupants from night ventilation, although the absence of internal heat gains during the daytime for the family profile allowed the cooling benefit to persist throughout the day and into the evening.

External fixed shading

External fixed shading above the windows was a very effective intervention and highly ranked for most cases. The standard depth of the shading (horizontal distance from the wall) was 1.0m, but where possible for east and west-facing windows the ground floor shading was extended to a depth of 2.0m by using retractible awnings (see Section 4.4). The semi-detached house had bay windows to the living room and main bedroom, which benefitted from the addition of the fixed shading and in particular the extended (2.0m) shading for east and west orientations for the living room. The overheating reduction due to fixed shading was comparable to that from external shutters and for west-facing living rooms with family occupancy was the highest ranked intervention. The fixed shading not only shaded the glazing, but also parts of the external brickwork, reducing some of the solar heat gains through the building fabric.

The effectiveness for terraced houses was reduced because it was assumed that shading at the front (above the living room windows) would be limited to 1.0m due to the proximity of the pavement and road. Similarly for flats, larger shading devices were excluded on grounds of practicality. However, the shallower flat windows (1.1m deep) allowed the fixed shading to shield the glazing from much of the solar radiation, even for east and west-facing windows.

The addition of fixed shading devices resulted in greater heating energy use. The lowest increase (1-2%) was in the terraced houses, where the glazed area as a proportion of external wall area was lowest and east/west orientations were restricted to 1.0m deep shading devices above the living room windows. For the other dwelling types fixed shading increased heating energy use by 7-10% when the living room windows were south-facing.

Internal blinds and curtains

The use of internal blinds and curtains reduced overheating, but to a lesser extent than external shutters. They were both most effective when the living room windows faced south, with curtains reducing overheating typically by 20-30% for this orientation, but by up to 57% for the ground floor flat. The solar reflective blinds were more effective than the fabric curtains and typical maximum reductions were around 10% higher. Both curtains and blinds were found to be higher ranked interventions in the semi-detached house, flats and detached house than the terraced houses. The glazed area in these dwellings was greater than in the terraced houses, therefore control of glazing solar heat gains was relatively more effective.

Low e triple-glazing

Low e triple-glazing with a low SHGC (see Section 4.5.0.4) was an effective intervention, reducing overheating by a similar amount to internal blinds and curtains.

In percentage reduction terms it was most effective for the ground floor flat (up to 53% reduction), but produced the largest actual reduction in degree hours for the detached house with elderly occupants, where the front west orientation overheating was reduced by 239 degree hours (33% reduction). For the other dwelling types low e triple-glazing reduced overheating by typically around 30%.

Low e triple-glazing had a lower U-value than the existing double-glazing installed in each base case dwelling. However, the low SHGC of the glazing reduced solar heat gains, which would have been beneficial during the heating season. The net effect was in most cases a small reduction in heating energy use, although in some situations the result was neutral. In the case of the end-terraced house and ground floor flat with south-facing windows the result was a slight increase (0.2-0.8%) in heating energy use. However, the effect in the detached house was different. The base case detached house had low e double-glazing with a high SHGC to comply with 2006 building regulations, which took advantage of passive solar heat gains and retained them within the dwelling. For the detached house changing the glazing to low SHGC low e triple-glazing resulted in heating energy use increasing by up to 12.5%.

One possible solution, which could also be considered for the other dwelling types, would be to fit high SHGC low e glazing to south-facing windows with fixed shading designed to block the high altitude summer sun from reaching the glazing but allowing solar heat gains from lower altitude spring, autumn and winter sun. Low SHGC low e glazing could then be fitted to east and west facades to control solar heat gains from the lower altitude sun, which is more difficult to shade effectively.

Loft insulation/upgraded roof

The detached house had 300mm of loft insulation to comply with modern building regulations (details in Section 3.3) and was not considered for an insulation upgrade.

The base case terraced and semi-detached houses had 100mm of loft insulation and the flats had 50mm of roof insulation. Increasing the level of loft or roof insulation had very little effect on total overheating for all dwelling types. In the case of the semi-detached house the extra loft insulation increased overheating in the main bedroom by a small amount (up to 3%) and in the case of the top floor flat, upgrading the flat roof to a modern insulated standard increased main bedroom overheating slightly more (up to 6%).

The base case terraced and semi-detached houses assumed 100mm of joist level insulation, which provided significant savings in heating energy use over as-built cases with no loft insulation. However, as the thickness of loft insulation increases there is a diminishing return on energy savings. Increasing the thickness from 100mm to 250mm, to reduce the roof U-value to 0.15 $W/m^2 K$, reduced heating energy use by 2-4% and was slightly more effective in the semi-detached house than the terraced houses. Upgrading the flat roof in the block of flats had almost no effect on energy use for the ground floor flat and reduced energy use by around 3% for the first floor flat. However, the roof was a major heat loss area for the top floor flat and in this case replacing the roof reduced heating energy use by 13-15%.

Wall insulation

No wall insulation upgrades were considered for the modern detached house and the terraced houses were limited to internal and external wall insulation. All insulation has the effect of both keeping heat in as well as out. External wall insulation has the benefit of shielding the outer brickwork from solar radiation as well as leaving internal thermal mass exposed for radiative cooling. Internal wall insulation removes the connection to the wall thermal mass, although this can have a benefit for bedrooms where the internal surfaces cool more quickly as the temperature drops overnight.

External wall insulation consistently outperformed internal and cavity wall insulation for the effect on total overheating exposure. Internal wall insulation was the worst performing type for the terraced and semi-detached houses and for the ground and first floor flats. In the case of terraced houses both external and internal wall insulation reduced overheating in all cases except for the end-terraced house where the front was west-facing and it was occupied during the daytime (elderly profile). In this case the addition of internal wall insulation increased overheating exposure by 18%.

In the case of the top floor flat, cavity wall insulation produced the greatest total overheating for south, east and west facing rooms (see the discussion in Section 7.2.1.9). In many cases the addition of wall insulation on its own increased the overheating exposure compared to the base case. In particular, for top floor flats all three types of wall insulation increased overheating for elderly occupants in south, east and west-facing rooms. However, insulation is essential for lower energy consumption in the heating season so must be included in a solution that integrates adaptation with mitigation. Fortunately it was still possible to reduce overheating by combining the wall insulation with other interventions (see below).

External and internal wall insulation (both specified to the same final wall U-value of 0.35 $W/m^2\,K$) produced approximately the same energy use reductions, which ranged from 36-51% depending on dwelling type and orientation. The greatest reductions were in the end-terraced house and the first floor flat. In both of these cases the heat loss area of the external wall was greater than other major heat loss areas, and wall insulation had a larger relative effect. The end-terraced house had more external wall area than the mid-terraced house and the first floor flat had occupied spaces above and below, therefore the floor and ceiling were not heat loss surfaces as they were in the ground and top floor flat respectively.

The final wall U-value with cavity insulation (0.57 $W/m^2\,K$) was higher than for internal or external insulation and therefore the energy use reductions lower at 29-42%. The greatest reductions were again seen in the first floor flat.

9.3.2 Effect of combined interventions

No single intervention could eliminate overheating in any of the cases and combined interventions were required to maximise overheating reduction. The methodology behind the combined intervention simulations was presented in Chapter 4. The retrofit toolkit (Appendix B) should be used to view the results referred to in this section.

In the Tier 1 dwellings (terraced houses, semi-detached house and ground floor flat - see Section 9.2.1) overheating in the base case versions was comparable and could be eliminated by a range of passive interventions[2]. Overheating in Tier 2 dwellings (detached house, first and top floor flats) was up to 10 times higher when comparing the worst and best performing dwelling in each Tier (Section 6.2.1). Tier 2 dwellings were also harder to treat and in almost all cases it was not possible to completely eliminate overheating with any package of interventions.

The same intervention combinations had different impacts on overheating reduction depending on the dwelling type, orientation and occupancy. Taking the example of a combination of three behavioural interventions: window rules, night ventilation and closing curtains during the daytime, the base case total overheating in the ground floor flat with elderly occupancy could be reduced by 62% to 111 degree hours for west-facing windows and by 89% to 12 degree hours for north-facing windows. In contrast, for the top floor flat the percentage reductions for the same orientations were much lower (29% west and 32% north) and the overheating exposure with the interventions applied remained very high at 635 and 420 degree hours respectively.

[2] For two of the semi-detached house orientations with family occupancy overheating could not be totally eliminated, but could be reduced by over 99% to 1 degree hour.

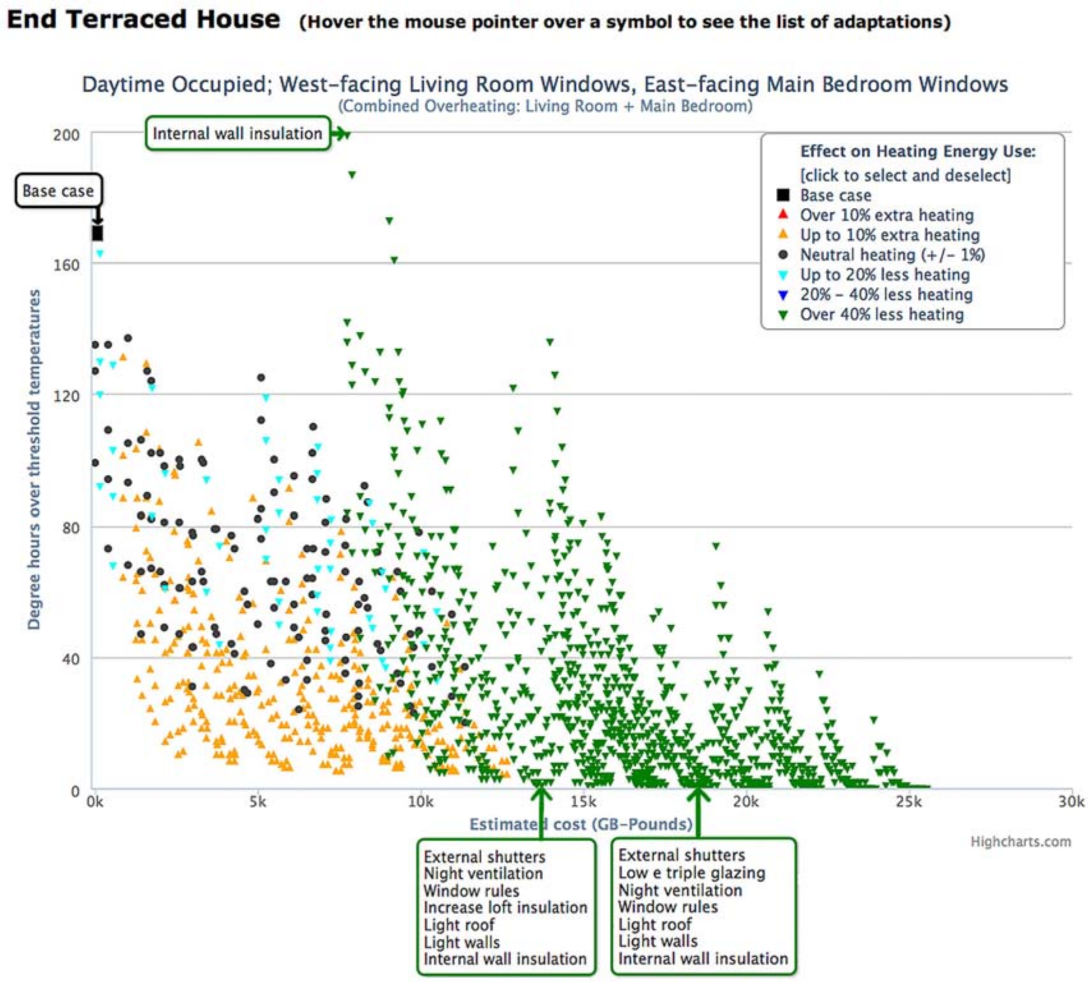

Figure 9.1 – Toolkit screenshot: combined interventions end-terraced house including internal wall insulation

The effect of wall insulation on overheating was discussed in Section 9.3.1 and it was noted that in many cases the addition of wall insulation resulted in greater overheating when applied as a single intervention. The combined intervention results demonstrated how wall insulation could be combined with other interventions to reduce overheating. For example, in the case of the end-terraced house with west-facing living room windows and elderly occupancy, the addition of internal wall insulation increased total overheating from the base case by 18% to 199 degree hours. Using the retrofit toolkit (Figure 9.1) for this case it can be seen that there were many intervention combinations which included internal wall insulation and which also substantially reduced total overheating. In fact overheating could be eliminated by choosing internal wall insulation combined with light walls, light roof, night ventilation, window rules, low e triple-glazing and external shutters. This would cost an estimated £18.7k and reduce heating energy use by 43%. However, the toolkit also shows that total overheating could almost be eliminated (reduced from 169 degree hours to 1 degree hour) by replacing the low e triple-glazing intervention with upgrading the loft insulation. This would cost an estimated £13.7k (£5k saving) and would decrease heating energy use by 45% (Figure 9.1).

Although some of the insulation interventions increased overheating, in general the effect of combining interventions was a reduction in overheating. The effect on heating energy use was different. Some interventions reduced heating energy use, whilst others had no effect or increased heating energy use. External and internal wall insulation upgrades were expensive and were also not generally the most effective interventions for overheating reduction. Often the best low cost interventions for overheating reduction required solar control interventions, some of which increased annual energy use and when used together the energy use increases were compounded. Using the toolkit shows that many of the lower cost intervention combinations increased heating energy use, often by greater than 10% (Figure 7.9).

As the budget increased wall insulation could be included in the interventions in addition to loft insulation (or the upgraded roof for the flats) and with a higher budget low e triple-glazing could be added. Maximum heating energy reductions of up to 61% were possible for the top floor flat and typically 40-50% for the semi-detached and terraced houses. The lack of any insulation interventions for the modern detached house, and the negative effect on heating energy use of the low e triple-glazing compared to the default low e double-glazing, resulted in no possible heating energy use reductions for the detached house with the interventions considered in this research.

9.4 Cost implications

The cost of reducing overheating and space heating energy use varied greatly between dwelling types and orientations, although generally the costs were similar for both occupancy profiles in each case. The costs used were estimates derived from a variety of sources (Section 4.8) and are likely to vary significantly in practice.

Dwellings that experienced the greatest overheating, such as the modern detached house and the top floor flat, required the greatest number of interventions to significantly reduce overheating. The larger roof, wall and glazed area resulted in solar protection interventions being more expensive for the detached house, where it cost up to £28.6k to achieve the maximum overheating reduction. However, the detached house did not include wall insulation upgrades and was not the most expensive dwelling type to treat. The inclusion of external wall insulation for the semi-detached house took the estimated cost of eliminating overheating to as much as £32.3k.

The top floor flat was the worst performing dwelling for overheating and required similar interventions to the semi-detached house to achieve the greatest overheating reduction. However, the smaller wall and glazed areas reduced the cost to a maximum £22.2k.

Costs also varied between different types of the same dwelling. The end-terraced house had a greater external wall area than mid-terraced house, therefore wall insulation and painting the external walls cost significantly more. For the end-terraced house it cost between £3.6k and £6.4k more to eliminate overheating than for the mid-terraced house, depending on orientation and occupancy profile.

Costs for the roof upgrade for the flats were based on a per flat installed cost, which was assumed to be shared equally amongst all 8 flats in the block. However, the benefits (or disadvantages) primarily affected the top floor flat residents.

The availability of inexpensive cavity wall insulation as an intervention for the flats and semi-detached house allowed the selection of low cost combined interventions that reduced both overheating and space heating energy use. This intervention was not available for the solid walled terraced houses, where the cost of reducing both overheating and heating energy use was higher.

It was not possible to eliminate overheating at any cost in the Tier 2 dwellings and typically the same package of interventions was required to achieve maximum overheating reduction for each orientation. The cost varied slightly due to the different cost of fitting external fixed shading (cost depends on orientation), but was typically within £2k.

For Tier 1 dwellings, where overheating could be eliminated by different combinations of interventions depending on orientation, the cost varied significantly. For example, elderly occupants in the south-facing semi-detached house could eliminate overheating for £19.2k, but the cost increased to £32.3k when the front was east-facing.

9.4.1 Payback and cost benefit

The payback period is the time taken for the initial cost of an intervention to be repaid through savings. For insulation and glazing upgrades there is a quantifiable benefit in terms of reductions in heating energy use and carbon emissions. The Energy Saving Trust (EST, 2012) and the Royal Institution of Chartered Surveyors (BCIS, 2008a) have published typical payback periods for a range of energy efficiency measures. However, the range of installed costs produces a large variation in payback periods, with estimates for some measures (e.g. solid wall insulation) not provided. Finance costs, the availability of grants and future energy prices will also have an impact on the payback period. The Department for Environment, Food and Rural Affairs (DEFRA) commissioned a report (BRE, 2007) to assess the cost effectiveness of a range of energy efficiency and carbon saving measures for homes. Their report found that payback periods will vary depending on whether other improvements

	Payback period (years)		
	RICS (BCIS, 2008a)	EST (EST, 2012)	BRE (BRE, 2007)
Cavity wall insulation	5	1 - 3	4.2* - 5.4
Loft insulation upgrade	13	2 +	16.7 - 21.1
Replace single glazing with double glazing	124	-	9.1 - 11.7
Solid wall insulation	-	-	14.2** - 17.6

* Lower costs are for individual measures applied to a stock average dwelling, higher costs assume a full range of measures has already been adopted

**The BRE report does not specify whether internal or external wall insulation was used for the calculations

Table 9.1 – Payback periods for energy efficiency upgrades

have already been carried out. For example, the report estimates a payback period of 4.2 years for cavity wall insulation applied to a stock average 3 bedroom semi-detached house, but this lengthens to 5.4 years for a similar house to which other energy efficiency upgrades have already been applied. Table 9.1 contains example payback periods from the sources mentioned above.

Also absent in the payback calculations is any consideration of climate change. As the UK climate warms heating energy use will fall and for some of the interventions with longer payback times (glazing upgrades and solid wall insulation) the payback period may be longer than forecast.

Many of the interventions modelled in this research had a clear benefit in improved comfort by reducing dwelling overheating, but with an accompanying increase in heating energy use. Payback periods cannot easily be estimated for interventions that improve comfort without using some quantifiable metric. In hotter climates, where mechanical cooling of dwellings is more common, the performance of interventions is often assessed in terms of cooling load reduction, from which a payback period can be calculated. In a future warmer UK climate, where uptake of air conditioning becomes more widespread, this method may be appropriate.

Solar reflective coatings may have further benefits beyond internal temperature reduction, including reduced maintenance through lower surface temperatures and wider benefits such as urban heat island mitigation if installed on sufficient properties.

A future development of the retrofit toolkit presented in this research could include payback calculations for single and combined interventions. Customised results could be generated, linking user defined intervention costs to heating energy use reduction, or a combination of heating and potential cooling load reduction.

9.5 Practicality of interventions

This research has concentrated on the effects of interventions, but it is worth noting some of the practical issues that may affect decision making and choice of interventions.

9.5.1 Behavioural interventions

The results demonstrate the benefit of behavioural interventions, which include the two ventilation strategies and glazing solar control by closing shutters, blinds or curtains. However, by definition these interventions rely on correct operation by the occupants.

The window rules intervention relies on occupants knowing when windows should not be opened. In hotter European countries it is a generally accepted that windows remain closed during the daytime in the summer. In the UK it may be necessary to educate occupants, possibly by including advice in the heat wave alerts or through installation of sensors to indicate when the windows should be closed, although this would then associate a cost with the intervention.

Night ventilation may be difficult to achieve in urban and city locations, where noise and security are likely to be issues. A possible solution would be to fit vents with low power fans to achieve the desired ventilation rate. Section 4.7.1 discussed how night ventilation is currently very effective for Northern European locations, such as the UK. However, the effectiveness is predicted to diminish as night time temperatures rise due to climate change and the urban heat island effect.

Residents occupying the dwellings during the daytime may not accept the loss of view due to closing shutters, blinds or curtains. There may also be a small increase in energy use and internal gains due to the use of lighting, although if low energy lighting is specified the increases will be low.

9.5.2 Solar reflective coatings

Solar reflective coatings on the walls and roof were found to be very effective in some cases, but their use may be limited by concerns with altering the external appearance. Dwellings in conservation areas or listed dwellings may not gain permission to apply the coatings. However, a further benefit for urban areas may be a reduction in the urban heat island effect, if sufficient buildings in an area are painted. The effectiveness of coatings may also diminish over time (Section 4.3).

9.5.3 Wall insulation

The choice of wall insulation type will be governed by a variety of factors, including dwelling construction type and location. The advantages and disadvantages of the three types of wall insulation are summarised in Table 9.2.

Type	**Advantages**	**Disadvantages**
External	Avoids internal disruption and loss of room volume	High installation cost
	Can achieve low U-values	Higher performance requires thicker insulation
	Render can be painted with solar control coating at the time of installation, improving overheating reduction	Difficult to install on a single dwelling within a row (terraced) or block (flats)
	Thermal bridging can be minimised if the whole external envelope is covered	Could be thermal bridging issues at boundaries if only one dwelling in a row or block is treated
	Can improve external appearance	Alters external appearance (may be issues in conservation areas or for listed buildings)
Internal	No change in external appearance	Loss of room volume
	Can achieve low U-values	Higher performance requires thicker insulation (more loss of room volume)
	Cheaper than external (usually)	Cost may be increased by redecoration
	Can more easily be fitted to a single dwelling in a row or block	Thermal bridging issues at the junction with internal solid partition walls
Cavity	Low cost, particularly with subsidies and grants	Not suitable for all dwellings with cavities (blocked or narrow cavities, or exposed locations)
	No disruption for residents	Limit to the lowest U-value that can be achieved
	No change of appearance (except small drill holes)	

Table 9.2 – Wall insulation advantages and disadvantages

9.5.4 Fixed shading

Fitting and maintenance of fixed shading devices may be a limiting factor, particularly for flats. Retractible devices (awnings) may degrade quicker than fixed overhangs and would also rely on correct operation by occupants (and may effectively become a behavioural intervention). Listed buildings and conservation areas may also prevent installation in some cases.

9.5.5 Low e triple-glazing

The cost may be prohibitive in many cases and difficult to justify in terms of heating energy saving payback. There may also be difficulties in obtaining glazing units in a style that is permitted in listed buildings or conservation areas.

9.6 Mitigation without adaptation

The UK government has committed to reducing greenhouse gas emissions by at least 80% (compared to 1990 levels) by 2050 (DECC, 2008). To achieve this in the domestic housing sector will require a huge investment to improve the thermal efficiency of the existing stock. The UK government estimate that 19.3 million dwellings could benefit from energy efficiency improvements and that to cut CO_2 emissions by an average 23% per dwelling would cost around £27 billion (CLG, 2011). The cost of greater emissions reductions would be significantly higher and another government report estimates the cost to achieve a 60% cut in CO_2 emissions would be around £200 billion (HM Government, 2010b).

Schemes such as Warm Front and the (soon to be launched) Green Deal (DECC, 2010b) are intended to assist the uptake of energy efficiency improvements through a series of grants and loans. The Green Deal lists insulation, glazing and draught proofing upgrades as eligible measures for fabric improvements, along with heating system upgrades and micro generation to reduce energy use (DECC, 2011). However, there is a risk that installation of some of the fabric upgrades without any consideration of summertime performance could lead to increased overheating during hot weather. The modelling results in this research (Chapters 6 and 8) show that the well insulated modern detached house used significantly less heating energy per unit floor area than the other dwelling types, but exhibited high levels of overheating during the heat wave period compared to the poorly insulated terraced and semi-detached houses.

The effects of climate change are expected to result in reduced heating energy use. Modelling by Gupta and Gregg (2012) predicts falls in heating energy use of 27% by the 2030s and 38% by the 2050s for a semi-detached house based in Oxford (similar to the semi-detached house used in this research). Collins et al. (2010) modelled heating and cooling demand in UK housing for the current climate through to the 2080s and predict that cooling demand in London will increase sharply, doubling by the 2050s and rising by over 3 times by the 2080s (although starting from a low base). Their research also shows that although heating demand is predicted to fall, CO_2 emissions level off in the latter half of the century as reductions in heating demand are offset by increased cooling demand.

With projected increases over the coming decades in both mean summer temperatures and the frequency and severity of heat waves, the result could be increased discomfort and heat stress problems due to overheating or, for those who can afford it, an increased uptake of mechanical cooling (air conditioning), negating some of the gains in energy efficiency. Davies and Oreszczyn (2012) highlight the problems associated with mitigation measures that do not consider climate adaptation, including poor indoor air quality associated with lower ventilation rates and increased overheating risk due to energy efficiency improvements. Retrofit decision making therefore needs to take account of the annual performance of dwellings, both in the current climate and during the lifetime of the building, to avoid or minimise the future need for mechanical cooling.

To explore the impact of retrofitting dwellings only considering heating energy and carbon emission reductions, tests were carried out on the solid walled end-terraced house. The simulations assessed the impact of implementing a high performance carbon emission mitigation retrofit, without considering heat wave adaptation measures. Selected combinations of overheating reduction interventions were then applied to these low carbon versions and the results compared to the modern detached house.

To produce a low carbon retrofit version of the end-terraced house the walls were insulated to the same U-value as the modern detached house (0.27 W/m^2 K), by increasing the thickness of the insulation layer to 0.08m and both internal and external insulation options were modelled. The default double-glazing was replaced with the same low e double-glazing used in the detached house (U-value 1.96 W/m^{2}K, SHGC 0.691) . The ground floor was also insulated to achieve a U-value of 0.2 W/m^2 K and the loft insulation increased to 0.3m. Extensive draught proofing was assumed, reducing background infiltration to 0.25 ACH. The base case terraced houses used in the main simulations already assumed some improvements, including double glazing, 0.1m loft insulation and reduced infiltration compared to as built. The carbon emission mitigation retrofit version reduced CO_2 emissions by 61% compared to the base case version used in the main simulations and by 71% compared to an as-built end-terraced house (single glazing, no loft insulation and infiltration 1.0 ACH).

Table 9.3 compares the overheating results for the worst case orientation for the end terraced house (front east-facing) and the modern detached house (front west-facing) assuming the elderly occupancy profile.

The low carbon retrofit of the end-terraced house increased the total overheating exposure during the heat wave period and the choice of wall insulation type had a significant impact, with internal wall insulation resulting in 28% higher overheating than external wall insulation. When internal wall insulation was specified the overheating reached 648 degree hours, approaching that of the modern detached house (721 degree hours), whilst overheating using external wall insulation was 507 degree hours.

Three packages of interventions were applied to reduce overheating. Each package included external fixed shading, night ventilation, window rules, light roof and light walls, in addition to either internal blinds, external shutters or curtains. When the low carbon retrofit included internal wall insulation, the overheating could not be reduced to the same level that was achieved for the version of the end-terraced house used in the main simulations. However, if external wall insulation was specified for the retrofit, overheating could be reduced to lower levels and almost eliminated (3 degree hours) using the intervention package with external shutters.

	Total overheating degree hours (living room plus main bedroom), elderly occupancy (with interventions cost)			
	End-terraced (front east-facing)			Modern detached (front west-facing)
	Version used in main simulations	Low carbon retrofit with internal wall insulation	Low carbon retrofit with external wall insulation	Version used in main simulations
Base case	288	648	507	721
With: **Internal blinds**, fixed shading, night vent, window rules, light roof, light walls	13 (£6.4k)	34 (£6.4k)	9 (£6.4k)*	63 (£12.3k)
With**: External shutters**, fixed shading, night vent, window rules, light roof, light walls	10 (£8.0k)	13 (£8.0k)	3 (£8.0k)*	28 (£15.4k)
With: **Curtains**, fixed shading, night vent, window rules, light roof, light walls	14 (£4.8k)	42 (£4.8k)	12 (£4.8k)*	75 (£9.7k)

*There would be a cost saving (approx £1,000) in solar reflective coating the external walls if the low carbon retrofit was carried out at the same time as the overheating retrofit for external wall insulation

Table 9.3 – Effect of carbon mitigation and overheating retrofit to end terraced house

The cost of the overheating retrofit packages for the end-terraced house are much lower than for the detached house due to the smaller wall and roof area and the smaller glazed area. The research shows that it is easier and cheaper to reduce overheating in a terraced house that has already been retrofitted to reduce carbon emissions if external wall insulation is fitted rather than internal wall insulation. The external wall insulation fitted in the low carbon retrofit assumed a standard render of similar solar absorptivity to the default brickwork. If a solar reflective render coating was specified instead of the standard render paint during the low carbon retrofit, the base case overheating would be reduced by 11% to 451 degree hours at a small extra cost at the time of installation.

9.7 Limitations

The results presented in this research allows users of the toolkit to gain an insight into the performance of a cross-section of dwelling types. The dwellings were chosen to be representative of the housing stock in London and South East England. However, in practice the built form, construction methods and upgrades to the fabric carried out since construction will vary significantly even across similar dwellings. Future research should expand on the uncertainty and sensitivity analysis (Section 5.8) to provide a range of possible results for each dwelling type to account for variations in construction materials.

Some of the simulation results will be transferrable to other similar house types, for example a Victorian solid walled semi-detached house is likely to perform in a similar way to the modelled end-terraced house. Other general observations from the results could also be transferred across different archetypes. Solid walls are effective conductors of solar heat gains and coating them with a solar reflective paint is likely to be effective for other solid wall dwellings. Similarly, dwellings with higher levels of insulation and air tightness are likely to experience higher levels of overheating, as observed in the modern detached house.

Some dwelling types were not included in this research, such as timber framed houses and bungalows, for which there are no comparable dwellings in the toolkit.

Expanding the range of dwelling types and variants of each dwelling (see Section 10.4.6) would allow users of the toolkit to select guidance that is better matched to their particular building.

The glazed area will have a significant impact on glazing solar heat gains and the relative effectiveness of interventions such as external shutters and fixed shading. Each simulation model assumed a fixed glazed area and future research should investigate the impact of varying the glazing ratio for each dwelling type.

The ventilation rates due to opening windows were set according to values in BS5925 (BSI, 1991 - see Section 5.3). In reality the ventilation due to opening windows will vary significantly, depending on the maximum openable area, the wind speed and how far the occupant chooses to open the windows (which in turn may be linked to wind speed, noise, security and air quality). To improve the representation of ventilation from open windows in modelling will require more detailed field studies, particularly for comparing urban and rural locations.

The weather data used in the simulations, both for the heat wave period (2003) and the CIBSE TRY weather file for heating energy simulations, was for London Heathrow. Across the Greater London area and South East England the local climate conditions will vary according to a variety of factors, including the urban heat island effect, where for example elevated night time temperatures are likely to reduce the effectiveness of night ventilation. Overheating simulations were only carried out for the 2003 heat wave period and future research should expand the simulations to include other heat wave periods (e.g. 1976 and 1995) as well as future weather using the UKCP09 probabilistic weather data. Results could also be presented to compare the effect and ranking order of interventions for heat wave periods and for whole summer overheating.

The two occupancy profiles (Section 2.6) were chosen to represent daytime occupied and daytime unoccupied dwellings. In practice there will be large variations, with some family occupancy during the daytime and some occasions when elderly residents leave their homes during the day. Different rooms may also be used at certain times of the day than those assumed in the profiles.

The costs of interventions (Section 4.8) were estimates derived from a variety of sources. The research found a large variation, depending on both the source and whether the costs were for individual householders or landlords. The cost information used in this research and in the retrofit toolkit is provided as a guide to compare typical installed costs for householders. It is likely to vary significantly in practice and payback periods (Section 9.4.1) will also affect the choice of interventions and should be included in future versions of the toolkit.

Finally, many people, including key stakeholders involved in the CREW project, are sceptical of results derived from computer simulations. The best way to convince them is through validation by comparing monitored data from real dwellings with simulation results. Further validation is therefore suggested, including the effect of interventions applied to a base case building.

9.8 Summary

This chapter has compared the simulation results across the dwelling types, orientations and occupancy profiles. The effectiveness of interventions was compared and the implications for heating energy use and cost discussed. Practical issues associated with interventions were also identified and the effect of retrofitting a thermally poor dwelling (end-terraced house) to modern standards, without considering overheating, was assessed.

The next chapter will distil the findings from this chapter and the three results chapters to present the conclusions and key messages from this research.

Chapter 10

Conclusions and suggestions for further work

10.1 Research summary

This research has expanded on previous research and publications addressing overheating in dwellings by systematically generating quantitative, holistic guidance for retrofitting UK dwellings. Four dwelling types, providing seven distinct variants, were modelled for two different occupancy profiles and four orientations to assess the effect of a range of passive interventions for reducing overheating during heat wave periods. Single and combined interventions were modelled and the effect on annual space heating energy use and cost were included in the analysis.

The research also produced a novel retrofit toolkit, which has been made publicly available online. The toolkit allows designers, decision makers and homeowners to select the most appropriate combination of interventions to reduce both overheating and space heating energy use at a given budget.

10.2 Key messages

A number of key observations and conclusions were drawn from the results of this research, which include:

- Overheating varied significantly between dwelling types, orientations and occupancy profiles. Two categories of dwelling were identified: Tier 1 (19th century terraced houses, 1930s semi-detached house and 1960s ground floor flat) and Tier 2 (1960s mid and top floor flats and the modern detached house). Tier 2 dwellings overheated between 2 and 10 times more than Tier 1 dwellings. For example occupants of top floor flats with west-facing rooms experienced 8 to 10 times the overheating exposure of those in ground floor flats with north-facing rooms. People who occupied the dwellings during the daytime (e.g. elderly or infirm) experienced typically double the overheating exposure of those who were out during the daytime (e.g. working adults and school children).

- Solar control interventions for windows and walls were found to be the most effective way of reducing overheating. Fitting external shutters was the most effective single intervention for most dwelling types, typically resulting in a 50% reduction in overheating exposure. The exception was the solid wall terraced houses, which benefitted most from solar control coatings applied to the external walls, although shutters were still very effective.

- Choice of wall insulation type was shown to be very important. External wall insulation consistently performed better than internal wall insulation for overheating reduction, with cavity wall insulation generally falling between the two. External wall insulation shields the outer brickwork from solar radiation and leaves existing thermal mass exposed on the inside to provide a radiative cooling benefit. Internal wall insulation removes the connection to the thermal mass and effectively traps heat gains inside the dwelling. However, this can be a benefit for bedrooms where the wall surface cools quicker as the air temperature drops at night.

- In some cases adding wall insulation could increase overheating compared to the base case. However, as part of a package of interventions, overheating can be significantly reduced or eliminated and heating energy use reduced by combining wall insulation with other measures.

- Some of the solar control interventions (solar reflective coatings and fixed shading) increased winter heating energy use. If dwellings already had low e double-glazing with a high SHGC (designed to allow passive solar gains and retain heat inside the dwelling) then upgrading to low SHGC low e triple-glazing increased winter heating energy use.

- Zero cost behavioural interventions, such as modifications to ventilation strategies and keeping curtains closed during the daytime, could significantly reduce overheating, whilst not increasing heating energy use. In the ground floor flat with north-facing living room and main bedroom windows, keeping the windows closed during hot periods (window rules) and closing the curtains during the daytime reduced overheating by 66% to 36 degree hours for elderly occupants.

- Tier 1 dwellings were easier to treat and overheating could be eliminated by a range of passive interventions. Tier 2 dwellings were harder to treat and overheating could not be eliminated with purely passive interventions at any cost.

- The cost of adaptation varied significantly depending on dwelling type, occupancy and orientation. To either eliminate or achieve the lowest possible overheating in each case cost an estimated: £0.8-4.4k (ground floor flat); £7-15k (mid-terraced house); £14-21k (end-terraced house); £19-22k (mid floor flat); £20-22k (top floor flat); £25-29k (detached house) and £19-32k (semi-detached house). East/west oreintations were more expensive to adapt than north/south orientations. In the case of the modern detached house, for example, base case overheating was higher for east/west orientations and the lowest possible overheating after adaptation remained higher than for north/south orientations. The cost of achieving the lowest overheating was also higher for east/west orientations (over £28k) than for north/south orientations (£25-26k). Orientation should therefore be considered when building (or choosing) new homes.

- Adaptation should be considered together with mitigation, both in design practice and regulations. If existing houses (e.g. solid wall terraced) are retrofitted for energy efficiency without considering summer use, overheating could increase dramatically. Subsequent corrective measures could be costly and energy efficiency may suffer as a result.

10.3 Research impact

The research project has engaged extensively with stakeholders over the last 3 years. Participation in numerous workshops and seminars has disseminated the research and the web toolkit is currently being assessed.

The web-based retrofit toolkit (Appendix B) provides housing designers, consultants, decision makers and researchers with an interactive facility to gain insights into the correlation between dwelling type, building construction, occupancy, orientation, overheating exposure, energy use and cost. The toolkit features in the latest London Climate Adaptation Strategy (Greater London Authority, 2011), which recommends its use by London's residential social landlords.

Quotes from stakeholders:

From London Climate Adaptation Strategy (Greater London Authority, 2011):

The CREW project has developed an online toolkit that can predict overheating in four different house types (detached, semi-detached, terraced and purpose-built flats). The toolkit can also be used to assess the impact of a range of 'passive' (non-powered) measures in managing overheating, the associated impact on space heating energy use and the relative cost benefits of individual and combined measures. This will allow landlords to identify an optimum mix of measures to manage overheating in their housing stock. The Mayor will encourage London's Registered Social Landlords to utilise this toolkit.

From the CREW project Final Assembly:

Prof. Li Shao and Stephen Porritt's work potentially the most interesting element – implications for building refurbishment and the Green Deal. Costings good as gives choices. Important it influences government. Emily Hay DCLG.

Gerry Cast – Lewisham Council. Key messages: "Ambitious, interdisciplinary approach and programme of research". CREW offers extraordinarily useful tools and a fascinating new approach with some outputs that will truly be the drivers for change in some urban areas, especially in Lewisham.

10.4 Recommendations for further research

10.4.1 Overheating thresholds

The limitations of the current CIBSE guidelines for overheating thresholds and the definition of an acceptable level of overheating were discussed in Section 2.3.3. When the CIBSE overheating task force has completed its review and issued new guidelines, which are likely to include adaptive thresholds, these could be applied in future research to quantify overheating.

10.4.2 Future climates

When simulation weather files are available that contain the most extreme heat wave periods predicted to occur under future climate scenarios, and when they have been certified for use by CIBSE in dynamic thermal modelling, they could be used in future simulations using the methodology developed in this research.

10.4.3 Further validation testing using monitored dwellings

Further detailed monitoring of real buildings, both with and without interventions, would contribute to modelling validation and increase confidence in the simulation outputs.

10.4.4 Uncertainty and sensitivity analysis

Some limited sensitivity analysis was carried out on software settings and modelling inputs. Further analysis is suggested to assess the range of uncertainty in the simulation output.

10.4.5 Additional interventions

The range of possible passive interventions is not limited to those selected for assessment in this research. The following interventions may be considered (amongst others) for evaluation in extended research.

One possible glazing solution to improve annual heating energy use, whilst still reducing summer overheating, would be to fit fully reversible glazing units to change the low e coating orientation depending on the season (Feuermann and Novoplansky, 1998). However, such units are uncommon and would add significantly to the cost.

Solar films for windows were initially considered in this research, they would be a lower cost solution than fitting low e glazing and could be applied to existing windows. However, the films can degrade and start to detach if not applied correctly. They would also reduce light transmission all year round and could lead to dim rooms and greater lighting energy use in the winter.

Thermochromic paints for external surfaces have been developed and tested (Karlessi et al., 2009), which change their absorptivity according to the air temperature, thereby not incurring the same penalty of extra winter heating energy use associated with standard reflective paints. They are however likely to be considerably more expensive than traditional solar reflective coatings.

Thermal mass can help to reduce the large swings in temperature experienced during hot weather (although this can have a negative effect for bedrooms where night time temperatures can remain high). Traditionally, additional thermal mass would need to be added at the construction stage, although it is possible to effectively add thermal mass by installing phase change materials (PCM) incorporated in wall or ceiling boards. They would be an expensive retrofit option, that could only realistically be considered during major refurbishment. Care would also need to be taken over selecting a suitable melting temperature, to ensure that the PCM was able to store and release the latent energy to its full potential. A night ventilation strategy would also be required to recharge the PCM.

The possibility of mixing types of wall insulation within one dwelling could solve some problems. For example internal wall insulation at the front to preserve original brickwork, with external insulation at the sides and rear. Future simulations should also use the latest Building Regulations final wall U-values required for alterations to existing dwellings.

Earth pipes are sometimes included in new low energy house designs, where air is drawn through clay pipes buried about 2.0m below the surface to pre-cool the ventilation air. This may be a potential retrofit intervention for dwellings with sufficient land, but would be an expensive option.

Ceiling fans can provide an effective temperature reduction of up to 2 K. It is not possible to model them directly in DTM software, but they should be considered before mechanical conditioning.

Low energy lighting was already assumed in this research, but further reductions in internal gains from more efficient appliances could help to reduce overheating. This is particularly important for modern dwellings, constructed to higher thermal standards with increased air tightness.

10.4.6 Additional variables

This research considered three simulation variables: dwelling type, orientation and occupancy profile. Further research could consider introducing extra variables, including:

- Dwelling configuration - the position, shape and size of rooms and the position and size of windows.
- External factors - such as neighbouring buildings, shade trees and the street geometry and albedo.
- The adaptive movement of occupants within the dwelling as a response to hot weather - i.e. the effect heat waves have on occupancy patterns and whether different rooms will be used for different functions (e.g. moving the bedroom to a downstairs room).

- Consider using a set of 'improved' base case dwellings, where for example recommended Green Deal improvements have already been carried out to assess the effect on overheating adaptation options.

However, including these additional variables in the existing modelling framework would produce a huge database of results and some simplifications would be required, such as selecting specific case studies.

Appendix A

Construction materials

A.1 Glazing material properties

	Layers	SHGC	Visible transmittance	U-value (glazing) W/m^2K	U-value (frame) W/m^2K
Pre 2002 double-glazing, uPVC frame (terraced, semi-detached, flats)	2 x 6mm 12mm air gap	0.742	0.801	2.72	3.48
Part L2 2006 double-glazing, uPVC frame (detached house)	2 x 3mm 13mm air gap	0.691	0.744	1.96	3.48
Low e triple-glazing, uPVC frame (all dwellings)	3 x 3mm (inner and outer coated) 2 x 6mm air gaps	0.472	0.66	1.57	3.48

Table A.1 – Glazing constructions

	Default double-glazing terraced, semi-detached, flats (pre 2002 uncoated)	Default double-glazing detached (Part L2 2006, low e)		Low e triple-glazing		
	Outer and inner panes	Coated outer pane	Inner pane	Coated outer pane	Uncoated middle pane	Coated inner pane
Thickness (m)	0.004	0.003	0.003	0.003	0.003	0.003
Solar transmittance at normal incidence	0.816	0.74	0.837	0.63	0.837	0.63
Front side solar reflectance at normal incidence	0.075	0.09	0.075	0.19	0.075	0.22
Back side solar reflectance at normal incidence	0.075	0.1	0.075	0.22	0.075	0.19
Visible transmittance at normal incidence	0.892	0.82	0.898	0.85	0.898	0.85
Front side visible reflectance at normal incidence	0.081	0.11	0.081	0.056	0.081	0.079
Back side visible reflectance at normal incidence	0.081	0.12	0.081	0.079	0.081	0.056
Infrared transmittance at normal incidence	0	0	0	0	0	0
Front side infrared hemispherical emissivity	0.84	0.84	0.84	0.84	0.84	0.1
Back side infrared hemispherical emissivity	0.84	0.2	0.84	0.1	0.84	0.84
Conductivity (W/mK)	1.0	0.9	0.9	0.9	0.9	0.9

Source: EnergyPlus database - all data is spectral average

Table A.2 – Glazing properties

A.2 Construction material properties

	Dwellings*	Conductivity W/m-K	Specific heat J/Kg-K	Density Kg/m^3
Brick (outer)	T,S,F,D	0.77	840	1700
Brick (inner)	T,S	0.56	850	1700
Render (external wall insulation)	T,S,F	0.57	1000	1300
Tiles (wall hanging)	S	1.5	1000	2100
Concrete blocks (wall)	T,F,D	0.51	1000	1400
Insulation (wall cavity)	D	0.034	1400	35
Insulation (wall cavity)	S,F	0.04	750	12
Insulation (wall internal/external)	T,S,F	0.025	1800	30
Plaster (walls)	T,S,F	0.57	1000	1300
Plasterboard (walls/ceiling)	T,S,F,D	0.21	1000	900
Concrete blocks (partitions)	D	0.19	1000	600
London clay (soil)	T,S,F,D	1.41	1000	1900
Brick slips (floor)	T,S,F	0.77	1000	1700
Cast concrete (floor)	T,S,F	1.35	1000	2000
Screed (floor)	T,S,F,D	0.41	1000	1200
Insulation (floor)	D	0.023	1000	30
Concrete blocks (floor)	D	0.22	1000	600
Underlay	T,S,F,D	0.10	1360	400
Carpet	T,S,F,D	0.06	2500	160
Floorboards	T,S	0.14	1200	650
Chipboard flooring	D	0.15	2093	800
Glass fibre quilt (loft)	T,S,F,D	0.04	840	12
Clay tile (roof)	T,S	1.00	800	2000
Concrete tile (roof)	D	1.5	1000	2100
Roofing felt	T,S,F,D	0.19	837	960
Insulation (roof)	F	0.04	1300	15
Plywood (flat roof)	F	0.13	1500	500
Fibreboard (upgrade roof)	F	0.14	1700	600
Asphalt (roof)	F	0.7	1000	2100
* Dwellings: T=terraced, S=Semi-detached, F=Flats, D=Detached				

Table A.3 – Thermophysical properties of construction materials

Appendix B

Retrofit toolkit

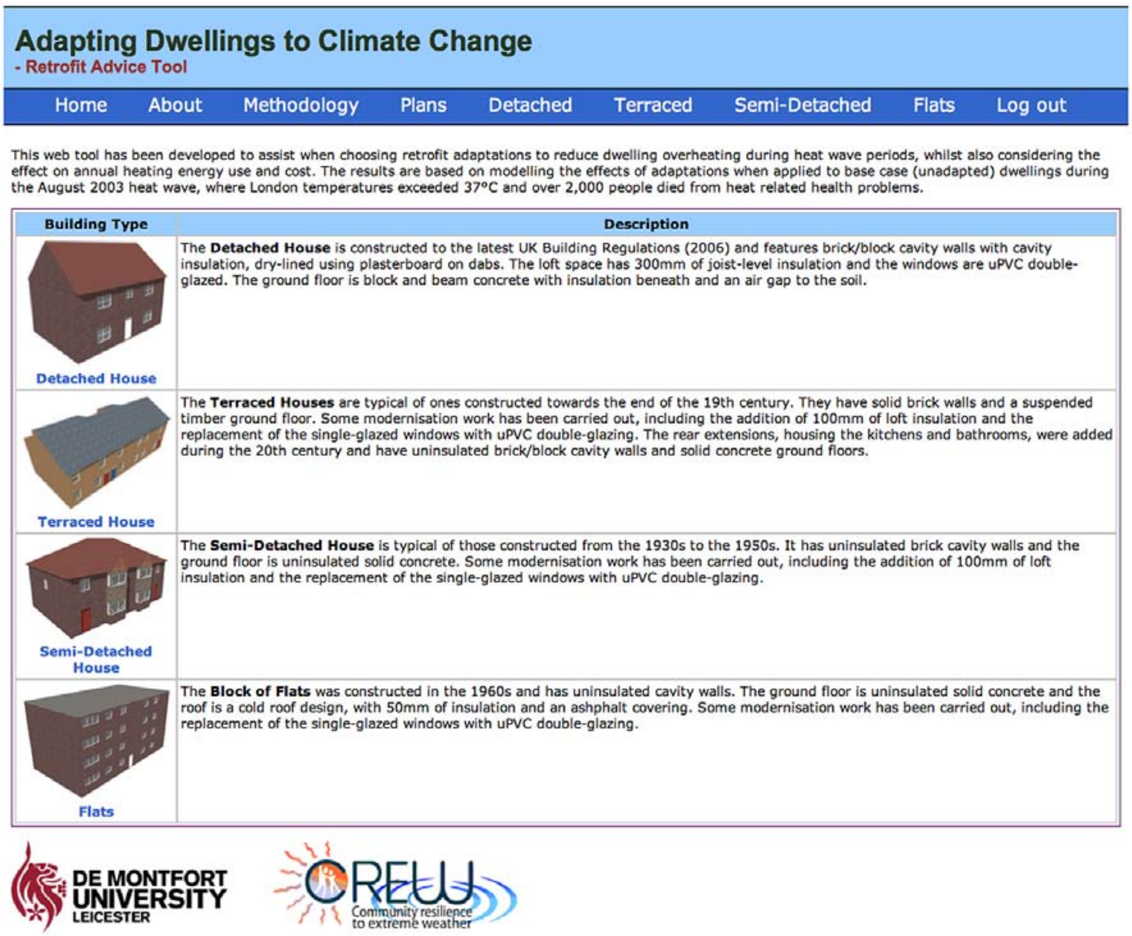

Figure B.1 – Toolkit screenshot: home page

The retrofit toolkit (Figure B.1) was produced to disseminate the research results as part of the CREW project. It can be accessed online at: www.iesd.dmu.ac.uk/crew and has also been supplied on CD-ROM within printed copies of this thesis (in a folder fixed inside the back cover). The toolkit, which consists of a series of linked HTML pages, allows the user to view the effect of single or combined interventions for each of the dwelling types, for the two occupancy profiles and four orientations. There are also pages providing a brief summary of the methodology, dwelling floor plans and a list of publications.

Instructions:

The CD-ROM contains the toolkit as a set of HTML files. The toolkit can be launched by double-clicking on the file: **index.html**, which should open a web browser on a PC or Mac with the toolkit home page. The contents of the disc can also be copied to a folder on the host computer and launched from that folder.

B.1 How to use the toolkit:

The occupancy profiles in the toolkit have been named daytime occupied (equivalent to elderly) and daytime unoccupied (equivalent to family). Some of the CREW project stakeholders were not familiar with the term *interventions*, this was replaced with the term *adaptations* in the toolkit.

The main page for each dwelling type contains a central bar chart showing the ranking order of single adaptations (interventions) for overheating reduction (Figure B.2). The default chart in each case shows the living room, with the front of the dwelling north-facing and with daytime occupancy (e.g. elderly). The options in the drop-down boxes allow selection of the living room, main bedroom or living room and main bedroom combined; four orientations and daytime occupied or unoccupied (e.g. family). The unadapted dwelling (base case) is highlighted in dark blue and any adaptations that result in greater overheating are highlighted as red bars. Hovering the mouse pointer over the adaptation descriptions on the right hand side shows a pop-up box with details about the adaptation.

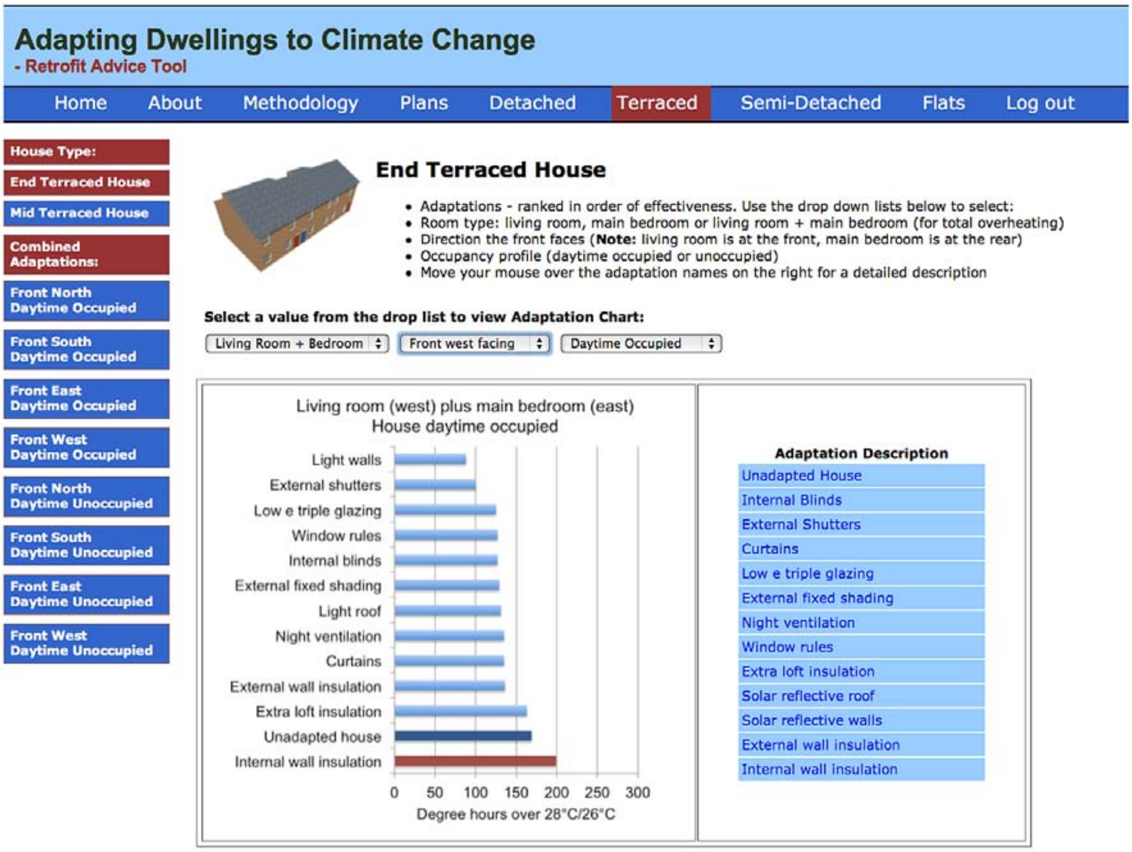

Figure B.2 – Toolkit screenshot: single interventions

The combined intervention results (Figure B.3) are accessed using the buttons on the left navigation area within each dwelling type and were produced using Highcharts (2012). Hovering the mouse pointer over any marker point in the scatter plots will display the interventions associated with that point. The colour and shape of the markers provides information about the heating energy use, which has been banded for ease of comparison. It is possible to deselect heating energy bands by clicking on them in the key box. This may help when viewing the results, for example to view only interventions that provide over a 40% reduction in heating energy use. In some areas of the scatter plots the points of interest are densely packed and overlap. Another useful Highcharts function is the ability to zoom an area of the plot by

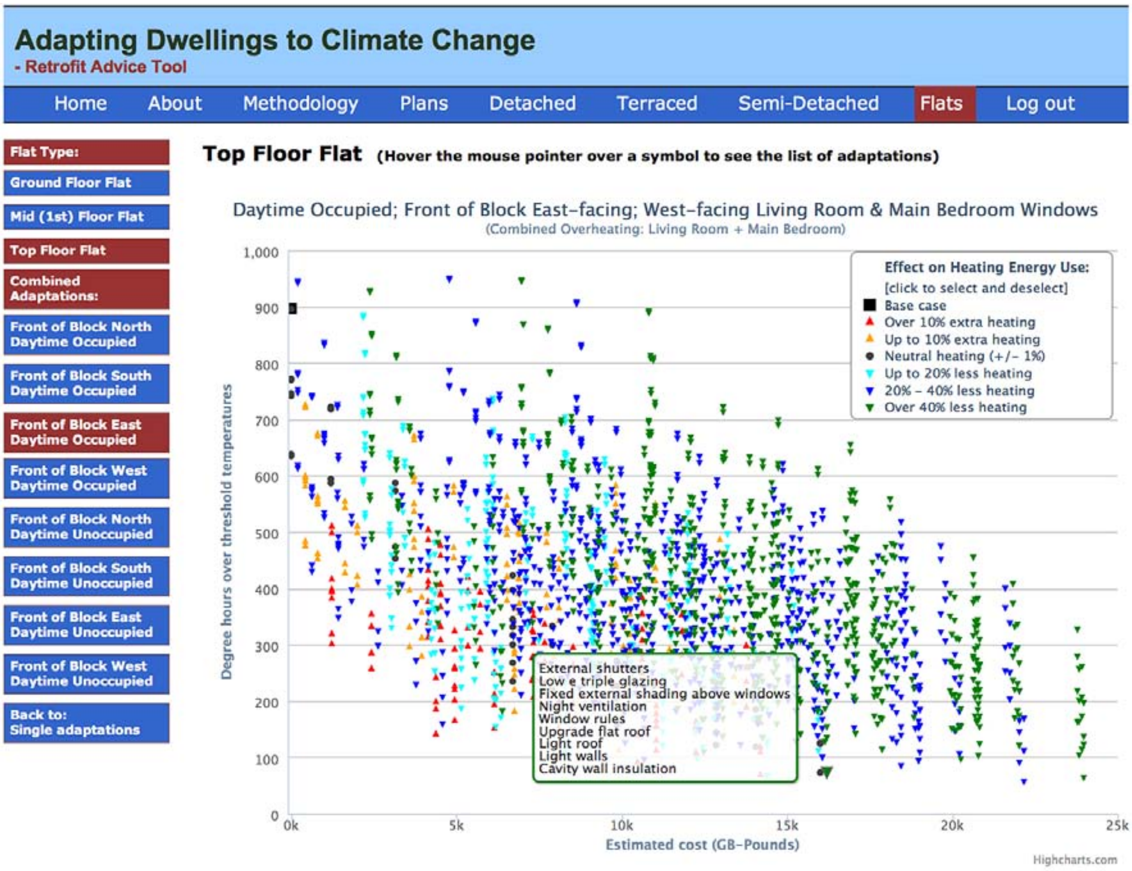

Figure B.3 – Toolkit screenshot: combined interventions

drawing a rectangle with the mouse. A 'reset zoom' text appears in the top right corner of the plot to return to the normal view.

The toolkit allows exploration of the results and in many cases there are intervention combinations that produce a similar overheating reduction at a similar cost, but which are better for space heating energy use. It may also be the case that certain interventions are not allowed, for example fitting external wall insulation in a conservation area, and the toolkit enables the exploration of alternative solutions.

Appendix C

Energy Management System (EMS)

C.1 EMS code for ventilation control

The effect of opening windows in each room (zone) in each dwelling was simulated by controlling the natural ventilation with outside air as described in Section 5.4. This appendix contains sample pieces of EMS code for just one of the rooms - the living room in the ground floor flat (Flat 2).

Figure C.1 contains the programming code for default ventilation control, where the windows are assumed to open when the room operative temperature exceeds 22°C and are fully open by 28°C, regardless of outside dry bulb temperature.

Figure C.2 contains the programming code for the window rules intervention, where the windows are prevented from opening if the outside dry bulb temperature is greater than the room operative temperature.

Figure C.3 contains the programming code for the night ventilation intervention, where windows are allowed to open at night (using the bedroom window opening schedule), whilst following the standard daytime rules.

Table C.1 contains the key to Figures C.1, C.2 and C.3.

ZoneTF2Living	Sensor name for Flat 2 living room operative temperature
4910	Room identifier (zone name) used in EnergyPlus
WinLiving	EMS sensor name for living room window opening schedule
WinBed1	EMS sensor name for main bedroom opening schedule (to set night opening hours)
10027 and 10017	EnergyPlus names for living room and main bedroom window opening schedules
F2LVent	EMS program name for Flat 2 living room natural ventilation
4910 Nat Vent	EnergyPlus identifier for natural ventilation control in Flat 2 living room
T_ControllerF2livingW	EMS program name for flat 2 living room ventilation control program
0.075441	Air change rate in $m^3s^{-1}$when windows are fully open, corresponds to 6 ACH
OAT	EMS sensor name for outside dry bulb temperature

Table C.1 – Key to Figures C.1,C.2

```
!-   ==========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:SENSOR ==================

EnergyManagementSystem:Sensor,
    ZoneTF2Living,                                           !- Name
    4910,                                                    !- Output:Variable or Output:Meter Index Key Name
    Zone Operative Temperature;                              !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    WinLiving,                                               !- Name
    10027,                                                   !- Output:Variable or Output:Meter Index Key Name
    Schedule Value;                                          !- Output:Variable or Output:Meter Name


!-   ==========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:ACTUATOR ================

EnergyManagementSystem:Actuator,
    F2LVent,                                                 !- Name
    4910 Nat Vent,                                           !- Actuated Component Unique Name
    Zone Ventilation,                                        !- Actuated Component Type
    Air Exchange Flow Rate;                                  !- Actuated Component Control Type


!-   ==========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER =====

EnergyManagementSystem:ProgramCallingManager,
    Temp controlled opening factor F2 living win,            !- Name
    BeginTimestepBeforePredictor,                            !- EnergyPlus Model Calling Point
    T_ControllerF2livingW;                                   !- Program Name 1


!-   ==========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM ==================

EnergyManagementSystem:Program,
    T_ControllerF2livingW,                                   !- Name
    IF WinLiving == 1.0 && ZoneTF2Living >= 28,              !- Program Line 1
    SET F2LVent = 0.075441,                                  !- Program Line 2
    ELSEIF WinLiving == 1.0 && ZoneTF2Living < 28 && ZoneTF2Living > 22,  !- A4
    SET F2LVent = 0.075441 * ((ZoneTF2Living - 22) / (28 - 22)),          !- A5
    ELSE,                                                    !- A6
    SET F2LVent = 0.0,                                       !- A7
    ENDIF;                                                   !- A8
```

Figure C.1 – EMS code for Flat 2 living room default ventilation

```
!-   ========== ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:SENSOR ===================

EnergyManagementSystem:Sensor,
    ZoneTF2Living,                                        !- Name
    4910,                                                 !- Output:Variable or Output:Meter Index Key Name
    Zone Operative Temperature;                           !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    WinLiving,                                            !- Name
    10027,                                                !- Output:Variable or Output:Meter Index Key Name
    Schedule Value;                                       !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    OAT,                                                  !- Name
    ,                                                     !- Output:Variable or Output:Meter Index Key Name
    Outdoor Dry Bulb;                                     >!- Output:Variable or Output:Meter Name

!-   ========== ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:ACTUATOR =================

EnergyManagementSystem:Actuator,
    F2LVent,                                              !- Name
    4910 Nat Vent,                                        !- Actuated Component Unique Name
    Zone Ventilation,                                     !- Actuated Component Type
    Air Exchange Flow Rate;                               !- Actuated Component Control Type

!-   ========== ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER =====

EnergyManagementSystem:ProgramCallingManager,
    Temp controlled opening factor F2 living win,         !- Name
    BeginTimestepBeforePredictor,                         !- EnergyPlus Model Calling Point
    T_ControllerF2livingW;                                !- Program Name 1

!-   ========== ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM ===================

EnergyManagementSystem:Program,
    T_ControllerF2livingW,                                                            !- Name
    IF WinLiving == 1.0 && ZoneTF2Living >= 28 && ZoneTF2Living > OAT,                !- Program Line 1
    SET F2LVent = 0.075441,                                                           !- Program Line 2
    ELSEIF WinLiving == 1.0 && ZoneTF2Living < 28 && ZoneTF2Living > 22 && ZoneTF2Living > OAT,  !- A4
    SET F2LVent = 0.075441 * ((ZoneTF2Living - 22) / (28 - 22)),                      !- A5
    ELSE,                                                                             !- A6
    SET F2LVent = 0.0,                                                                !- A7
    ENDIF;                                                                            !- A8
```

Figure C.2 – EMS code for Flat 2 living room window rules intervention

```
!-   ==========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:SENSOR ===================

EnergyManagementSystem:Sensor,
    ZoneTF2Living,                                          !- Name
    4910,                                                   !- Output:Variable or Output:Meter Index
Key Name
    Zone Operative Temperature;                             !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    WinLiving,                                              !- Name
    10027,                                                  !- Output:Variable or Output:Meter Index
Key Name
    Schedule Value;                                         !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    WinBed1,                                                !- Name
    10017,                                                  !- Output:Variable or Output:Meter Index
Key Name
    Schedule Value;                                         !- Output:Variable or Output:Meter Name

EnergyManagementSystem:Sensor,
    OAT,                                                    !- Name
    ,                                                       !- Output:Variable or Output:Meter Index
Key Name
    Outdoor Dry Bulb;                                       >!- Output:Variable or Output:Meter Name

!-   ==========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:ACTUATOR =================

EnergyManagementSystem:Actuator,
    F2LVent,                                                !- Name
    4910 Nat Vent,                                          !- Actuated Component Unique Name
    Zone Ventilation,                                       !- Actuated Component Type
    Air Exchange Flow Rate;                                 !- Actuated Component Control Type

!-   ==========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAMCALLINGMANAGER =====

EnergyManagementSystem:ProgramCallingManager,
    Temp controlled opening factor F2 living win,           !- Name
    BeginTimestepBeforePredictor,                           !- EnergyPlus Model Calling Point
    T_ControllerF2livingW;                                  !- Program Name 1

!-   ==========  ALL OBJECTS IN CLASS: ENERGYMANAGEMENTSYSTEM:PROGRAM ===================

EnergyManagementSystem:Program,
    T_ControllerF2livingW,                                                          !- Name
    IF WinLiving == 1.0 && ZoneTF2Living >= 28 && ZoneTF2Living > OAT,              !- Program Line 1
    SET F2LVent = 0.075441,                                                         !- Program Line 2
    ELSEIF WinLiving == 1.0 && ZoneTF2Living < 28 && ZoneTF2Living > 22 && ZoneTF2Living > OAT,  !- A4
    SET F2LVent = 0.075441 * ((ZoneTF2Living - 22) / (28 - 22)),                    !- A5
    ELSEIF WinBed1 == 1.0 && ZoneTF2Living > 22,                                    !- A6
    SET F2LVent = 0.075441,                                                         !- A7
    ELSE,                                                                           !- A8
    SET F2LVent = 0.0,                                                              !- A9
    ENDIF;                                                                          !- A10
```

Figure C.3 – EMS code for Flat 2 living room night ventilation intervention

Appendix D

Constructing EnergyPlus weather files

Table D.1 lists the weather data required to construct EnergyPlus format EPW weather files along with the data available from the weather source files used. Only relevant weather variables have been included, i.e. those that are required to complete the EPW files or to calculate any missing variables that are not directly provided in the source files.

The data to construct the London Heathrow 2003 weather file was provided by the Met Office via the British Atmospheric Data Centre (UK Meteorological Office, 2011c). This did not contain solar radiation, horizontal infrared radiation or opaque sky cover data. As discussed in Chapter 5 the decision was made to use solar data from a neighbouring weather station, the London Weather Centre. This data had to be converted from Kjoules/m^2 to Wh/m^2 and could then be used to calculate the direct normal radiation and diffuse horizontal radiation using the formulae in equations D.1 and D.2, from U.S. Department of Energy (2011a). The solar altitude data was provided by the CIBSE weather files for London Heathrow.

Weather variable	Used in EnergyPlus	Units	2003 Heathrow	2003 London Weather Centre	CIBSE 1976/1995	DMU weather station	NREL East Midlands
Hourly data	■	-	■	■	■	■	■
Dry bulb temperature	■	°C	■				
Dew point temperature	■	°C	■				
Wet bulb temperature		°C	■				
Relative humidity	■	%				■	
Atmospheric pressure	■	Pa	■			■	
Horizontal infrared radiation	■*	Wh/m^2					
Direct normal radiation	■	Wh/m^2				■	
Diffuse horizontal radiation	■	Wh/m^2				■	
Global solar irradiation		$Kjoules/m^2$		■			
Diffuse solar irradiation		$Kjoules/m^2$		■			
Wind direction	■	degrees	■			■	
Wind speed	■	m/s	■			■	
Total sky cover	■	tenths	■				■
Opaque sky cover	■*	tenths					
Solar altitude		degrees			■		

* Note: EnergyPlus requires either horizontal infrared radiation or opaque sky cover in order to calculate the effective sky temperature, if one is missing the other is used.

Table D.1 – Weather data for EnergyPlus EPW files

$$Global_{horizontalradiation} = Direct_{horizontalradiation} + Diffuse_{horizontalradiation} \tag{D.1}$$

$$Direct_{normalradiation} = \frac{Direct_{horizontalradiation}}{SIN(Solar_{height})} \tag{D.2}$$

The Met Office London Heathrow file also did not contain relative humidity data, though it did contain the dewpoint temperature as well as the dry bulb temperature, allowing calculation of relative humidity. Relative humidity (RH) is the ratio of actual vapour pressure (e) over the saturated vapour pressure (e_s) (Equation D.3).

$$RH = 100\frac{e}{e_s} \tag{D.3}$$

Lawrence (2005) provides a variety of methods for calculating relative humidity, including one using the Magnus formula to calculate the values of e and e_s (Equations D.4 and D.5). The fixed coefficient values in the equations were derived by Alduchov and Eskridge (1996) and claim to provide accurate values (less than 0.4% error) for temperatures between -40°C and 50°C. In the formulae T is the dry bulb temperature and $T_d$is the dewpoint temperature.

$$e = 6.11 \exp\left(\frac{17.625T_d}{243.04 + T_d}\right) \tag{D.4}$$

$$e_s = 6.11 \exp\left(\frac{17.625T}{243.04 + T}\right) \tag{D.5}$$

The completed fields were then substituted into an existing London Heathrow EPW weather file to create the heat wave year weather files.

The simulation weather file for Leicester, used in Appendix E, was constructed using the same procedure.

Appendix E

EnergyPlus validation

Chapter 5 discussed how empirical validation of DTM software is one of the most important methods for testing the accuracy of simulation outputs and for providing confidence in the results of modelling exercises.

During the first few months of the research a short validation exercise was carried out using a studio apartment in Leicester (Flat 68, Queen St., in which the author was living). The aim was to gain confidence in the simulation process and ensure that the simulation methods adopted would provide reasonable results. Unfortunately the occupied period did not cover any hot weather events and therefore it was not possible to evaluate the modelling process under heat wave conditions.

Extensive monitoring of an elderly care home was also undertaken during the course of the PhD, with the hope that it would provide a further opportunity to validate EnergyPlus, including during a summer period. However, several issues with unpredictable operation (e.g. heating systems being left on during the summer and internal doorways to unmonitored zones being wedged open) resulted in the data being unusable, although the exercise provided a useful insight into the issues surrounding monitoring of occupied buildings to inform future validation tests.

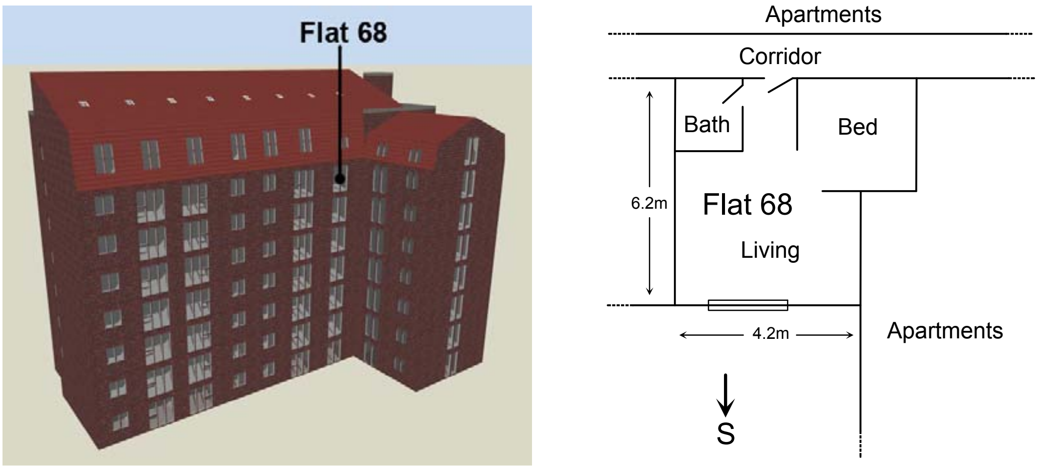

Figure E.1 – Queen St. apartment building simulation model and Flat 68 floor plan

The apartment monitoring took place for a ten day period from the 17th to the 26th September, 2008. Daytime peak outdoor dry bulb temperatures ranged between 14 and 21 °C and night temperatures dropped to between 8 and 13 °C. The hourly living room air temperature was recorded using a Hobo data logger (stated accuracy of ±0.5 °C (Onset, 2012)). Window opening, blind control, occupancy and TV use were also recorded and used to create schedules for use in EnergyPlus. De Montfort University has a weather station located approximately 1 mile from the apartment building that provided most of the weather data required to construct a simulation weather file, although one important variable, cloud cover, was not available. A compromise solution involved substituting cloud data from East Midlands Airport (approximately 15 miles from Leicester). This was not ideal due to the possible differences in cloud cover between the two locations, which could have a large impact on solar heat gains during the daytime and radiative exchanges at night. The methods outlined in Appendix D were used to construct the simulation weather file.

The building was modern, having been completed in early 2008. The simulation model (Figure E.1) was constructed using copies of non-scale floor plans, which were corrected with extensive site measurements to ensure that zone volumes, wall areas and glazing dimensions were accurately represented in the simulation model. The building had 8 stories, constructed of a concrete frame with brick and block insulated cavity walls. Each storey was separated by a concrete slab floor/ceiling and internal partitions were constructed of concrete blocks. It was not possible to obtain accurate information regarding the construction materials used, therefore material properties were assigned according to building regulations in force at the time of construction (Office of the Deputy Prime Minister, 2006b) by selecting the appropriate templates in DesignBuilder (Part L2 2006 medium weight). Different construction materials could have an impact on the thermal mass and hence the building response to changing external conditions. Solar gains may also be different depending on the external surface absorptivity and glazing material properties. Table E.1 contains a summary of the construction details used in the model.

The apartment had one large pair of windows in the living room (effectively French windows with a false balcony railing). There was no other ventilation provision in the apartment, therefore cross-ventilation was not possible. The large windows could not be latched open and the only way of securing the open window was by wedging it with books on the sill. In this position the opening was measured at 50mm and the SAP value of 0.5 ACH for single sided ventilation with a 50mm opening was used in the simulation when the window was open (Building Research Establishment, 2010). The DesignBuilder model was built using the scheduled ventilation option, consistent with the method chosen for the main research. However, the assumed ventilation rate with the window open may have varied according to wind speed and direction.

The monitored period was before the heating season and there was no heating used in the apartment. Hot water provision was by a small electric heated reservoir under the sink and by an electric shower, with no distributed hot water system to contribute to building heat gains.

	Construction	U-value W/m^2 K	Solar absorptivity
External walls	Brick/block with 0.08m insulated cavity and internal plaster 0.013m Total thickness 0.293m	0.35	0.7
Roof	Occupied roof space (8th floor), tiles with foam insulation, plasterboard lined	0.16	0.7
Ground floor	Cast concrete 100mm over stone chippings to clay, insulated. Carpet with underlay	1.1	0.6
Intermediate floors	Concrete slab 0.1m	-	0.6
Internal partitions	Medium weight concrete blocks	-	0.5
Glazing	Part L 2006 double-glazing: 0.003m clear glass with 0.013m air gap SHGC 0.69, direct solar transmission 0.62, light transmission 0.74	2.0 (inc. frame)	-
Window frames	Grey aluminium	(above)	0.7
External doors	Front doors for flats lead to unconditioned communal hallways	-	-

Table E.1 – Queen St. construction details

The simulation was run using EnergyPlus directly from DesignBuilder. The results presented here used Version 2.3.5, running EnergyPlus Version 6, the same versions used in the main research. The same simulation settings used in the main research (adaptive surface convection algorithms and 12 simulation timesteps per hour - see Section 5.2.1) were selected for use in this test.

Figure E.2(a) shows the outdoor dry bulb temperature from the DMU weather station, the living room air temperature from the Hobo data logger and the predicted living room air temperature from DesignBuilder/EnergyPlus. Figure E.2(b) shows an expanded chart of the monitored and simulated living room air temperature, with dotted lines showing ±0.5 °C of the monitored temperature (the stated accuracy of the Hobo logger). For most of the time the difference between the monitored and simulated temperatures was within ±0.5 °C, with mean temperature only differing by 0.1 °C. The maximum temperature difference was 1.4 °C, with the largest differences

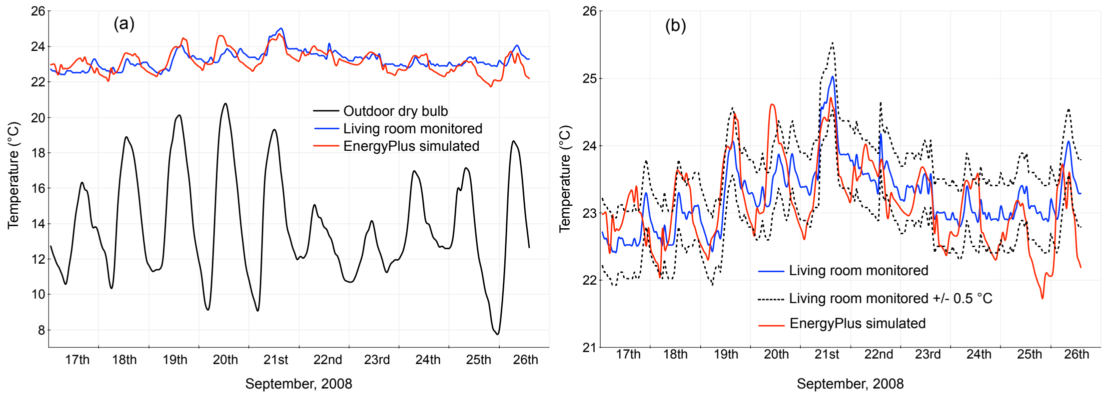

Figure E.2 – Queen St. Living room temperatures: monitored and simulated

occurring on the last two nights. Some of the differences could be the result of variations in local weather conditions, with cloud cover data being one issue, as discussed above. Ventilation rates through the open window may also have varied due to wind speed and direction.

The lack of accurate local weather data and uncertainties regarding the construction details of the Queen St. apartment make this short validation exercise of limited value. The monitored period (September) did not allow testing of the simulation during periods of higher solar gain and external temperature. Further validation exercises are recommended in future research (Section 10.4). This would require detailed monitoring in controlled buildings of known construction and particularly (for application to this research) during periods of hot weather. A sensitivity analysis on the simulation inputs would enable identification of the important (sensitive) parameters.

Appendix F

Vernacular dwelling design in warmer climates

This appendix presents a brief overview of how dwellings have historically been designed to provide a comfortable home in hotter parts of the world, demonstrating the use of some of the measures proposed as interventions in this research.

F.0.1 Europe

The climate predicted for Southern England later this century will be closer to the current climate of more southerly European regions, depending on the assumed emissions scenario. Research by Gaterell and McEvoy (2005) used current climate data for Milan to represent a low emissions 2080s climate and Rome as a proxy for a high emissions scenario, an approach also adopted by de Wilde et al. (2008). It is useful, therefore, to study how buildings in Southern European cities have been constructed and adapted to cope with warmer climates.

Roaf et al. (2005) looked at the evolution of buildings in the southern Italian city of Naples over the last 2,000 years and concluded that modern buildings have far less passive adaptive opportunities when compared to the vernacular architecture of the city, in fact for modern air-conditioned buildings they conclude that adaptation to hot weather is limited to closing internal blinds and adjusting the air-conditioning. Traditionally, Neapolitan buildings employed high thermal mass construction and open layouts to encourage cross ventilation. Some even employed galleried thermal buffer spaces and stack ventilation strategies to draw cool air up from the the basements.

Figure F.1 – Mediterranean house features

Some of the features found in Southern European vernacular dwellings can only be considered for new developments, for example narrow streets for building shading and high thermal mass construction. However, other design features, such as light walls, shutters and fixed shading (Figure F.1), which are common features of many European dwellings, can be considered as retrofit options suitable for the UK in a warming climate.

F.0.2 Japan

A period of study in Japan during the research gave the opportunity to investigate Japanese housing and how that has developed to cope with hot weather. Japanese summers regularly reach temperatures over 30 °C, but the main difference between Japanese and British warm weather is the much higher levels of humidity in Japan.

Traditional Japanese houses (Figure F.2) were built using a post and beam construction method, with room dimensions based on multiples of the tatami mat (approx.

1.9m x 0.95m). This construction method allowed for flexible, open plan room layouts, using movable screens. Combined with large external openings, this allowed the passage of winds (known as 'Tsuufuu') through the house for natural cross ventilation. The need to protect from solar radiation was also well understood, using external shutters. Traditional houses also usually had wide eaves, which protect from higher solar angle radiation in the summer. Semi-external veranda areas acted as buffer spaces, protecting the main house from the summer sun and providing useful work spaces in the winter. Older traditional houses often had thatched roofs, which also acted as an insulating buffer from the sun.

Figure F.2 – Traditional Japanese house

During the 20th century many of the principles employed in traditional Japanese houses were abandoned in favour of Western style construction methods, with poor solar shading and closed room layouts. The advent of air conditioning and cheap energy meant that houses could be cooled easily. However, rises in energy prices and concerns about contributions to global warming from electricity production, have resulted in tighter building regulations in Japan, which has led to a renewed interest in many of the traditional cooling techniques for houses. The Japanese tradition of demolishing and rebuilding houses on a generational timescale (Barlow et al., 2003) also means that adaptations to climate change issues are easier to implement for the Japanese housing stock.

Modern Japanese homes (Figure F.3) often have light coloured walls and employ lightweight construction methods (low thermal mass). For houses that are mostly unoccupied during the day a high thermal mass construction would place a heavy load on the air conditioning system. Small secure windows that can be left open at night are now common in new houses and skylight windows provide a means of venting the warm air as it rises through the house. Thought is also being given to the outside environment around the houses, by using cool surfaces and optimum positioning of planted areas (including roof gardens) to use evapotranspiration for cooling.

Figure F.3 – Modern Japanese houses

Appendix G

Publications

Peer reviewed journal papers:

Stephen Porritt, Li Shao, Paul Cropper, Chris Goodier. Adapting Dwellings for Heat Waves. Sustainable Cities and Society. Vol. 1(2) pp 81-90, 2011.

S. M. Porritt, P. C. Cropper, L. Shao and C. I. Goodier. Ranking of interventions to reduce dwelling overheating during heat waves. Energy and Buildings (In Press) 2012.

Peer reviewed conference papers:

Porritt, S.M., Shao, L., Cropper, P.C. and Goodier, C.I. Occupancy patterns and their affect on interventions to reduce overheating in dwellings during heat waves. Proceedings of Conference: Adapting to Change: New Thinking on Comfort. Network for Comfort and Energy Use in Buildings, Windsor, April 2010.

S.M. Porritt, L. Shao, P.C. Cropper and C.I. Goodier. Ranking of interventions to reduce dwelling overheating during heat waves. Proceedings of Conference: Passive and Low Energy Cooling of Buildings (PALENC), Rhodes, September 2010.

S. M. Porritt, L. Shao, P. C. Cropper and C. I. Goodier. Assessment of interventions to reduce dwelling overheating during heat waves considering annual energy use and cost. Proceedings of Conference: CIBSE Technical Symposium, De Montfort University, Leicester UK – 6th and 7th September 2011.

Other conference papers:

S. M. Porritt, L. Shao, P. C. Cropper, and C. I. Goodier. Building orientation and occupancy patterns and their effect on interventions to reduce overheating in dwellings during heat waves. Proceedings of Conference: Energy and Sustainable

Development: 1st Annual IESD PhD Conference. De Montfort University, Leicester, UK, 21st May 2010.

Other publications:

Porritt, S., Goodier, C. I., and Shao, L. Briefing: Heat wave coping measures for housing. Proceedings of the Institution of Civil Engineers: Energy. Vol.162(3) pp 101-103, 2009.

Porritt, S.M., Shao, L., Cropper, P.C. and Goodier, C.I. Adapting UK dwellings for heat waves. Health Protection Agency Chemical Hazards and Poisons Report. Vol.16 pp 48-50, 2010.

Bibliography

Acclimatise (2010). *Rising to the Challenge - The City of London Climate Change Adaptation Strategy. First Published May 2007 Revised and Updated January 2010.* Acclimatise, for the City of London Corporation, London.

Alduchov, O. A. and Eskridge, R. E. (1996). Improved Magnus form approximation of saturation vapour pressure. *Journal of Applied Meteorology*, 35(4):601–609.

Allen, E. A. and Pinney, A. A. (1990). *Standard dwellings for modelling: details of dimensions, construction and occupancy schedules (BEPAC Technical Note 90/2.* Building Environmental Performance Analysis Club, Building Research Establishment, Garston, Watford, UK.

Andersen, R., Toftum, J., Klaus, K., and Olesen, B. (2009). Survey of occupant behaviour and control of indoor environment in Danish dwellings. *Energy and Buildings*, 41(1):11–16.

Anderson, B. R., Chapman, P. F., Cutland, N. G., Dickson, C. M., Henderson, G., Henderson, J. H., Iles, P. J., Kosmina, L., and Shorrock, L. D. (2008). Bredem-12 model description 2001 update. Technical report, BRE Press, Watford UK.

ANSI/ASHRAE (2010). *Standard 55-2010 – Thermal Environmental Conditions for Human Occupancy (ANSI approved).* American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ARCC (2012). Adaptation and Resilience in a Changing Climate Research Network. Online: http://www.ukcip-arcc.org.uk/ Last accessed 25th March, 2012.

Artmann, N., Gyalistras, D., Manz, H., and Heiselberg, P. (2008). Impact of climate warming on passive night cooling potential. *Building Research and Information*, 36(2):111–128.

Artmann, N., Manz, H., and Heiselberg, P. (2007). Climatic potential for passive cooling of buildings by night-time ventilation in Europe. *Applied Energy*, 84:187–201.

Arup (2008). Your home in a changing climate. Retrofitting existing homes for climate change impacts. Report for policy makers. Technical report, Three Regions Climate Change Group, London.

ASHRAE (2009). *Handbook: Fundamentals. S.I. Edition.* American Society of Heating, Refrigerating and Air-Conditioning Engineers, Atlanta, GA.

Barlow, J., Childerhouse, P., Gann, D., Hong-Minh, S., Naim, M., and Ozaki, R. (2003). Choice and delivery in housebuilding: lessons from Japan for UK housebuilders. *Building Research and Information*, 31(2):134–145.

Barry, C. J. and Elmahdy, A. H. (2007). Selection of optimum low-e coated glass type for residential glazing in heating dominated climates. Institute for Research in Construction, National Research Council Canada. Available online: www.nrc-cnrc.gc.ca/obj/irc/doc/pubs/nrcc50253/nrcc50253.pdf Last accessed 25th March, 2012.

BCIS (2008a). *The Greener Homes Price Guide.* Number ISBN 978 1 904829 67 6. The Building Cost Information Service, London.

BCIS (2008b). *The Property Makeover Price Guide: Organising and Budgeting for Home Improvers & Developers.* Number ISBN 978 1 904829 80 5. The Building Cost Information Service, London, 2nd edition.

Belcher, S. B., Hacker, J. N., and Powell, D. S. (2005). Constructing design weather data for future climates. *Building Services Engineering Research and Technology*, 26(1):pp49–61.

Bio Intelligence Service (2010). European Commission (DG ENER) Preparatory Studies for Ecodesign Requirements of EuPs. Lot 22: Domestic and commercial ovens. Available to download from: www.ecocooking.org Last accessed 25th March, 2012.

Boardman, B., Darby, S., Killip, G., Hinnells, M., Jardine, C. N., Palmer, J., and Sinden, G. (2005). *40% House.* Environmental Change Institute, University of Oxford.

Brager, G. S., Paliaga, G., and de Dear, R. (2004). Operable Windows , Personal Control , and Occupant Comfort. *ASHRAE Transactions*, 110(2):17–35.

BRE (2007). Delivering cost effective carbon saving measures to homes. Building Research Establishment report for DEFRA. Available online: www.decc.gov.uk/assets/decc/11/about-us/science/4074-delivering-cost-effective-saving-measures-to-homes.pdf Last accessed 9th June 2012.

BRE (2010). *Cool roofs and their application in the UK. Information Paper 13/10.* Building Research Establishment Publications, Garston, Watford, UK.

BRE (2011a). *Passivhaus Primer.* Building Research Establishment, Watford, UK.

BRE (2011b). Simplified Building Energy Model (SBEM) software, Building Research Establishment. Available online: www.ncm.bre.co.uk Last accessed 25th March, 2012.

BSI (1991). *British Standard Code of practice for Ventilation principles and designing for natural ventilation*. British Standards Institution, London.

BSI (2008). *BS EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics*. British Standards Institute, London.

Building Research Establishment (2010). *The Government's Standard Assessment Procedure for Energy Rating of Dwellings*. Building Research Establishment (for UK Department of Energy and Climate Change), Garston, UK, 2009 edition.

Capon, R. and Hacker, J. (2009). Modelling climate change adaptation measures to reduce overheating risk in existing dwellings. In *Eleventh International IBPSA Conference*, pages 1276–1283, Glasgow, Scotland.

Chudley, R. and Greeno, R. (2010). *Building Construction Handbook*. Number ISBN: 978-1-85617-805-1. Butterworth-Heinemann (Elsevier), Oxford, UK, 8th edition.

CIBSE (2005). Climate change and the indoor environment: Impacts and adaptation. Technical Report TM36, The Chartered Institute of Building Services Engineers (Pricipal authors: Hacker, J.N., Holmes, M.J., Belcher, S.B., and Davies, G.D.), London.

CIBSE (2006). *Guide A: Environmental Design*. The chartered Institute of Building Services Engineers, London.

CIBSE (2010a). *How to manage overheating in buildings: A practical guide to improving summertime comfort in buildings*. The Chartered Institution of Building Services Engineers, London.

CIBSE (2010b). Keeping cool in a heatwave: top tips for building users. Available online: www.cibseknowledgeportal.co.uk Last accessed 25th March, 2012.

CLG (2010). *Housing and Planning Statistics 2010*. Department for Communities and Local Government Publications. Available online: www.communities.gov.uk Last accessed 25th March, 2012.

CLG (2011). English housing survey housing stock report 2009. Department for Communities and Local Government. Available online: www.communities.gov.uk/documents/statistics/pdf/1937212.pdf Last accessed 10th June, 2012.

Coley, D. (2008). Representing Top-hung Windows in Thermal Models. *International Journal of Ventilation*, 7(2):151–158.

Coley, D., Kershaw, T., and Eames, M. (2012). A comparison of structural and behavioural adaptations to future proofing buildings against higher temperatures. *Building and Environment*, (In press).

Collins, L., Natarajan, S., and Levermore, G. (2010). Climate change and future energy consumption in UK housing stock. *Building Services Engineering Research and Technology*, 31(1):75–90.

Crawley, D. B., Lawrie, L. K., Winkelmann, F. C., Buhl, W. F., Huang, Y. J., Pedersen, C. O., Strand, R. K., Liesen, R. J., Fisher, D. E., Witte, M. J., and Glazer, J. (2001). EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings*, 33:319–331.

CREW (2011). Community Resilience to Extreme Weather Project. EPSRC grant: EP/F036442/1. Website: http://www.extreme-weather-impacts.net.

Davies, M. and Oreszczyn, T. (2012). The unintended consequences of decarbonising the built environment: A uk case study. *Energy and Buildings*, 46:80–85.

de Wilde, P., Yaqub, R., and Beck, M. (2008). Uncertainties in predicting the impact of climate change on thermal performance of domestic buildings in the UK. *Building Services Engineering Research and Technology*, 29(1):7–26.

DECC (2008). Climate Change Act 2008. Department of Energy and Climate Change. Available online: www.decc.gov.uk/en/content/cms/legislation/cc_act_08/cc_act_08.aspx Last accessed 8th June, 2012.

DECC (2010a). Household Energy Efficiency Delivery Model - Assessment of Impacts. Department of Energy and Climate Change. Available online: www.decc.gov.uk/publications/ Last accessed 25th March, 2012.

DECC (2010b). The Green Deal: A summary of the Government's proposals. Department of Energy and Climate Change. Available online: www.decc.gsi.gov.uk Last accessed 25th March, 2012.

DECC (2011). What measures does the green deal cover? Department of Energy and Climate Change. Available online: www.decc.gov.uk Last accessed 8th June, 2012.

DEFRA (2011). Weather Generator Version 2.0. Online: http://ukclimateprojections.defra.gov.uk/content/view/858/500/ Last accessed 25th March, 2012.

Department for Communities and Local Government (2009a). *English House Condition Survey 2007 Annual Report*. Number ISBN 978-14098-1783-3. Department for Communities and Local Government, London (also available online: http://www.communities.gov.uk/housing/housingresearch Last accessed 25th March, 2012.

Department for Communities and Local Government (2009b). English House Condition Survey Public Dataset 2007. On CD - Product code: 09ACST06138, EHCS project team, CLG, Eland House, London SW1E 5DU.

Department for Communities and Local Government (2010). *English Housing Survey Housing Stock Report 2008*. Department for Communities and Local Government, London.

Department of Health (2007). Heating and ventilation systems health technical memorandum 03-01: Specialised ventilation for healthcare premises. The Stationery Office, London.

DesignBuilder (2011). DesignBuilder software www.designbuilder.co.uk Last accessed 25th March, 2012.

DesignBuilder (2011). Version 2 documentation. Available online at www.designbuilder.co.uk/helpv2/ Last accessed 25th March, 2012.

DfES (2003). *Building Bulletin 87: Guidelines for Environmental Design in Schools*. Department for Education and Skills, 2nd edition.

ESRU (2011). ESPr simulation software, Energy Systems Research Unit, University of Strathclyde. Available online: www.esru.strath.ac.uk/Programs/ESP-r.htm Last accessed 25th March, 2012.

EST (2005). *CE129 Energy efficiency best practice in housing: Reducing overheating – a designer's guide*. Energy Saving Trust, London.

EST (2009). Solid wall insulation supply chain review. Purple Market Research for the Energy Saving Trust and the Energy Efficiency Partnership for Homes Available from: www.eeph.org.uk/resources/ Last accessed 25th March, 2012.

EST (2012). Home improvement products guide. Energy Saving Trust. Online: www.energysavingtrust.org.uk/Home-improvements-and-products/Home-insulation-glazing Last accessed 9th June, 2012.

Fanger, P. O. (1970). *Thermal comfort: analysis and applications in environmental engineering*. Danish Technical Press, Copenhagen, Denmark.

Feuermann, D. and Novoplansky, A. (1998). Reversible low solar heat gain windows for energy savings. *Solar Energy*, 62(3):169–175.

Frich, P., Alexander, L. V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A. M. G., and Peterson, T. (2002). Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research*, 19:193–212.

Gasparrini, A. and Armstrong, B. (2002). The impact of heat waves on mortality. *Epidemiology*, 22(1):68–73.

Gaterell, M. R. and McEvoy, M. E. (2005). The impact of climate change uncertainties on the performance of energy efficiency measures applied to dwellings. *Energy and Buildings*, 37:982–995.

Georgios, K., Clarke, J., and Strachan, P. (2007). Impact of using different models in practice - a case study with the simplified methods of ISO 13790 standard and detailed modelling programs. In *Proceedings: Building Simulation 2007*, number 2006, pages 39–46. IBPSA.

Givoni, B. (1994). *Passive and low energy cooling of buildings.* Van Nostrand Reinhold,, New York ; London :.

Glover, P. (2009). *Building Surveys.* Number ISBN: 978-1-85617-606-4. Butterworth-Heinemann (Elsevier), Oxford, UK, 7th edition.

Greater London Authority (2010). The draft climate change adaptation strategy for London: Public consultation draft. Available online at www.london.gov.uk/climatechange/ (downloaded 20th April, 2010, no longer available to download), London.

Greater London Authority (2011). Managing risks and increasing resilience The Mayor's climate change adaptation strategy. Available online: www.london.gov.uk/sites/default/files/Adaptation-oct11.pdf Last accessed 25th March, 2012, Greater London Authority, City Hall, London.

Gupta, R. and Gregg, M. (2012). Using UK climate change projections to adapt existing English homes for a warming climate. *Building and Environment*, (in press).

Hacker, J. N., Belcher, S. E., and Connell, R. K. (2005). *Beating the Heat: Keeping UK Buildings Cool in a Warming Climate. UKCIP Briefing Report.* UKCIP, Oxford.

Hacker, J. N., de Saulles, T. P., Minson, A. J., and Holmes, M. J. (2008). Embodied and operational carbon dioxide emissions from housing: A case study on the effects of thermal mass and climate change. *Energy and Buildings*, 40:375–384.

Hacker, J. N. and Holmes, M. J. (2007). Thermal comfort: climate change and the environmental design of buildings in the United Kingdom. *Built Environment*, 33(1):97–114.

Hajat, S., Kovats, R. S., Atkinson, R. W., and Haines, A. (2002). Impact of hot temperatures on death in london: a time series approach. *Journal of Epidemiology and Community Health*, 56:367–372.

Haldi, F. and Robinson, D. (2008). On the behaviour and adaptation of office occupants. *Building and Environment*, 43(12):2163–2177.

Halewood, J. and de Wilde, P. (2008). Simulation-based Assessment of the Prospects of Cool Paints in the Built Environment in the UK. In *PLEA 2008 – 25th Conference on Passive and Low Energy Architecture, Dublin, 22nd to 24th October 2008.*

Health Protection Agency (2008). *Health effects of climate change in the UK 2008 - An update of the Department of Health report 2001/2002*. Department of Health Publications, London.

Highcharts (2012). Interactive javascript charts for web projects. Available from: www.highcharts.com Last accessed 24th March, 2012.

HM Government (2010a). *The Building Regulations 2010. Approved document L1B Conservation of fuel and power in existing dwellings*. NBS, RIBA Enterprises Ltd., London.

HM Government (2010b). Low Carbon Construction Innovation and Growth Team Final Report. Available online: www.bis.gov.uk/assets/biscore/business-sectors/docs/l/10-1266-low-carbon-construction-IGT-final-report.

Hodgson, G. (2008). *An introduction to Passivhaus: A guide for UK application. IP 12/08*. Building Research Establishment, Watford, UK.

Holmes, M. J. and Hacker, J. N. (2007). Climate change, thermal comfort and energy: Meeting the design challenges of the 21st century. *Energy and Buildings*, 39:802–814.

Hulme, M., Jenkins, G. J., Lu, X., Turnpenny, J. R., Mitchell, T. D., Jones, R. G., Lowe, J., Murphy, J. M., Hassell, D., Boorman, P., McDonald, R., and Hill, S. (2002). Climate Change Scenarios for the United Kingdom: The UKCIP02 Scientific Report. Technical report, Tyndall Centre for Climate Change Research, School of Environmental Sciences, University of East Anglia, Norwich, UK.

IES (2011a). Apache-Tables Virtual Environment 5.9. Online: www.iesve.com/downloads/help/Thermal/ApacheTables.pdf Last accessed 25th March 2012.

IES (2011b). Integrated Environmental Solutions Virtual Environment software www.iesve.com Last checked 25th March, 2012.

INCA (2011). Insulated Render and Cladding Association. Online: www.inca-ltd.org.uk Last accessed 25th March, 2012.

Inkarojrit, V. and Paliaga, G. (2004). Indoor climatic influences on the operation of windows in a naturally ventilated building. In *Plea 2004 - Thw 21st Conference on Passive and Low Energy Architecture*, number September, pages 19 – 22, Eindhoven.

Jackson, A. and Day, D. (2002). *Period House: An Owner's Guide*. Number ISBN: 0-00-712761-8. HarperCollins, London.

Jenkins, D., Peacock, A., and Banfill, P. (2009a). Will future low-carbon schools in the UK have an overheating problem? *Building and Environment*, 44(3):490–501.

Jenkins, G., Murphy, J., Sexton, D., Lowe, J., Jones, P., and Kilsby, C. (2009b). *UK Climate Projections: Briefing report*. UK Climate Impacts Programme, Met Office Hadley Centre, Exeter, UK.

Johnson, H., Kovats, R. S., McGregor, G., Stedman, J., Gibbs, M., and Walton, H. (2005). The impact of the 2003 heat wave on daily mortality in England and Wales and the use of rapid weekly mortality estimates. *Eurosurveillance*, 10(7-9):168–171.

Jones, P., Harpham, C., Kilsby, C., Glenis, V., and Burton, A. (2010). Online Weather Generator report. Online: http://ukclimateprojections.defra.gov.uk/content/view/941/500/ Last accessed 15th March, 2012.

Karlessi, T., Santamouris, M., Apostolakis, K., Synnefa, A., and Livada, I. (2009). Development and testing of thermochromic coatings for buildings and urban structures. *Solar Energy*, 83(4):538–551.

Kolokotroni, M., Gowreesunker, B. L., and Giridharan, R. (2011). Cool roof technology in london: An experimental and modelling study. *Energy and Buildings*, In Press.

Kolokotroni, M., Zhang, Y., and Watkins, R. (2005). The London heat island and building cooling design. In *Passive and Low Energy Cooling for the Built Environment*, pages 743–748, Santorini, Greece.

Koppe, C., Kovats, S., Jendritzky, G., and Menne, B. (2004). *Heat-waves: risks and responses. Health and Global Environmental Change Series, No.2*. World Health Organization, Copenhagen, Denmark.

Langdon, D., editor (2011). *Spon's Architects' and Builders' Price Book*. Spon Press, UK, 136th edition.

Lawrence, M. G. (2005). The relationship between relative humidity and the dewpoint temperature in moist air: A simple conversion and applications. *Bulletin of the American Meteorological Society*, pages 225–233.

Lee, S. E. and Sharples, S. (2008). An analysis of the urban heat island of sheffield – the impact of a changing climate. In *PLEA 2008 – 25th Conference on Passive and Low Energy Architecture, Dublin, 22nd to 24th October 2008*.

Liddament, M. W. (2001). *Technical Note AIVC 53: Occupant Impact on Ventilation*. Internaional Energy Agency - INIVE eeig, Brussels, Belgium.

Lomas, K. J. and Eppel, H. (1992). Sensitivity analysis techniques for building thermal simulation programs. *Energy and Buildings*, 19:21–44.

Lomas, K. J., Eppel, H., Martin, C., and Bloomfield, D. (1994). Empirical validation of thermal building simulation programs using test room data. Vol. 1, Final Report. Technical Report IEA21RN399/94, International Energy Agency.

Macdonald, I. A. (2002). *Quantifying the Effects of Uncertainty in Building Simulation*. PhD thesis, Deparment of Mechanical Engineering, University of Strathclyde.

Macdonald, I. A., Clarke, J. A., and Strachan, P. A. (1999). Assessing uncertainty in building simulation. In *Proceedings: Building Simulation 1999*, pages 113–119, Kyoto, Japan. IBPSA.

Marshall, D. and Worthing, D. (2006). *The Construction of Houses*. EG Books, London, 4th edition.

Mavrogianni, A., Davies, M., Batty, M., Belcher, S. E., Bohnenstengel, S. I., Carruthers, D., Chalabi, Z., Croxford, B., Demanuele, C., Evans, S., Giridharan, R., Hacker, J. N., Hamilton, I., Hogg, C., Hunt, J., Kolokotroni, M., Martin, C., Milner, J., Rajapaksha, I., Ridley, I., Steadman, J. P., Stocker, J., Wilkinson, P., and Ye, Z. (2011). The comfort, energy and health implications of London's urban heat island. *Building Services Engineering Research and Technology*, 32(1):35–52.

Mavrogianni, A., Davies, M., Chalabi, Z., Wilkinson, P., Kolokotroni, M., and Milner, J. (2009). Space heating demand and heatwave vulnerability: London domestic stock. *Building Research & Information*, 37(5):583–597.

Mavrogianni, A., Wilkinson, P., Davies, M., Biddulph, P., and Oikonomou, E. (2012). Building characteristics as determinants of propensity to high indoor summer temperatures in london dwellings. *Building and Environment*, (in press).

Maxim (2012). i-button temperature loggers. www.maxim-ic.com/datasheet/index.mvp/id/4088 Last accessed 15th March, 2012.

Mayor of London (2006). *London's Urban Heat Island: A Summary for Decision Makers*. Greater London Authority.

McGregor, G. R., Pelling, M., Wolf, T., and Gosling, S. (2007). *Using science to create a better place. The social impacts of heat waves. Science Report SC20061/SR6*. Environment Agency, Bristol, UK.

Menne, B. and Matthies, F. (2009). Improving public health responses to extreme weather/heat-waves – EuroHEAT. Technical report, World Health Organization Europe, Copenhagen, Denmark.

Murphy, J. M., Sexton, D. M. H., Jenkins, G J Booth, B. B. B., Brown, C. C., Clark, R. T., Collins, M., Harris, G. R., Kendon, E. J., Betts, R. A., Brown, S. J., Humphrey, K. A., McCarthey, M. P., McDonald, R. E., Stephens, A., Wallace, C., Warren, R., Wilby, R., and Wood, R. A. (2009). *UK Climate Change Projections Science Report: Climate change projections*. Number ISBN 978-1-906360-02-3. Met Office Hadley Centre, Exeter, UK.

National Health Service (2011). *Heatwave Plan for England*. The Department of Health, London.

Neymark, J. and Judkoff, R. (2002). International energy agency building energy simulation test and diagnostic method for heating, ventilating, and air-conditioning equipment models (hvac bestest), vol. 1: Cases e100-e200. Technical Report NREL/TP-550-30152, National Renewable Energy Laboratory, Golden, CO, USA.

Nicol, F., Humphreys, M. A., and Roaf, S. (2012). *Adaptive therml comfort: principles and practice*. Number ISBN: 978-0-415-69159-8. Routledge, Taylor and Francis Group, Abingdon, UK.

Nicol, F., Rijal, H., Humphreys, M., and Tuohy, P. (2007). Characterising the use of windows in thermal simulation. In *Second PALENC conference and 28th AIVC conference on building low energy cooling and advance ventilation technologies in the 21st century*, volume 2, pages 27–29.

Ofcom (2010). UK children's media literacy. Available online from: http://stakeholders.ofcom.org.uk/binaries/research/media-literacy/ukchildrensml1.pdf Last accessed 21st March, 2012.

Office for National Statistics (2003). United Kingdom Time Use Survey, 2000. Online: Available to registered users from: www.esds.ac.uk/findingData/snDescription.asp?sn=4504 Last accessed 25th March, 2012.

Office of the Deputy Prime Minister (2006a). Housing Health and Safety Rating System Operating Guidance. Available online: www.communities.gov.uk/documents/housing/pdf/142631.pdf Last accessed 25th March, 2012.

Office of the Deputy Prime Minister (2006b). *The Building Regulations 2000. Conservation of Fuel and Power Part L1A conservation of fuel and power in new dwellings 2006 Edition*. NBS for the Office of the Deputy Prime Minister.

Office of the Deputy Prime Minister (2006c). *The Building Regulations 2000. Conservation of Fuel and Power Part L1B conservation of fuel and power in existing dwellings 2006 Edition*. NBS for the Office of the Deputy Prime Minister, London.

Onset (2012). Hobo pendant data loggers. Online: www.onsetcomp.com/products/data-loggers/ua-001-64 Last accessed 8th June 2012.

Orme, M. and Palmer, J. (2003). Control of overheating in future housing - design guidance for low energy strategies. Technical report, Faber Maunsell for the DTI Partners in Innovation Programme, St. Albans.

Orme, M., Palmer, J., Irving, S., and FaberMaunsell Ltd (2003). Control of overheating in well insulated housing. In *Proceedings of the CIBSE/ASHRAE Conference (24-26 September 2003) in Building Sustainability, Value and Profit, Edinburgh*.

Parsons, K. (2003). *Human thermal environments*. CRC Press, London, 2nd edition.

Peacock, A. D., Jenkins, D. P., and Kane, D. (2010). Investigating the potential of overheating in UK dwellings as a consequence of extant climate change. *Energy Policy*, 38(7):3277–3288.

Porritt, S. M. (2011). Web Toolkit. www.iesd.dmu.ac.uk/crew.

Raja, I. A., Nicol, J. F., McCartney, K. J., and Humphreys, M. A. (2001). Thermal comfort: use of controls in naturally ventilated buildings. *Energy and Buildings*, 33:235–244.

Richardson, I., Thomson, M., and Infield, D. (2008). A high-resolution domestic building occupancy model for energy demand simulations. Link to associated Excel workbook: http://hdl.handle.net/2134/3112. *Energy and Buildings*, 40(8):1560–1566.

Rijal, H. B., Tuohy, P., Nicol, F., Humphreys, M. a., Samuel, A., and Clarke, J. (2008). Development of an adaptive window-opening algorithm to predict the thermal comfort, energy use and overheating in buildings. *Journal of Building Performance Simulation*, 1(1):17–30.

Rijal, H. P., Tuohy, P., Humphreys, M. A., Nicol, J. F., Samuel, A., and Clarke, J. A. (2007). Using results from field surveys to predict the effect of open windows on thermal comfort and energy use in buildings. *Energy and Buildings*, 39:823–836.

Riley, M. and Howard, C. (2002). *Construction Technology 1: House Construction*. Number ISBN: 978-0-333-80456-8. Palgrave MacMillan, Basingstoke, Hampshire, UK.

Roaf, S., Crichton, D., and Nicol, F. (2005). *Adapting Buildings and Cities for Climate Change*. Number ISBN: 0-7506-5911-4. Architectural Press (Elsevier), Oxford, UK.

Rock, I. A. (2005). *The 1930s House Manual*. Number ISBN 1 84425 214 0. Haynes Publishing, Sparkford, Somerset, UK.

Santamouris, M., Sfakianaki, A., and Pavlou, K. (2010). On the efficiency of night ventilation techniques applied to residential buildings. *Energy and Buildings*, 42(8):1309–1313.

Semenza, J. C., Rubin, C. H., Falter, K. H., Selanikio, J. D., Flanders, W. D., Howe, H. L., and Wilhelm, J. L. (1996). Heat related deaths during the july 1995 heat wave in chicago. *The New England Journal of Medecine*, 335:84–90.

Smith, C., Lindley, S., and Levermore, G. (2009). Estimating spatial and temporal patterns of urban anthropogenic heat fluxes for uk cities: the case of manchester. *Theoretical and Applied Climatology*, 98(1-2):19–35.

Solomon, S., Qin, D., Manning, M., Alley, R. B., Berntsen, T., Bindoff, N. L., Chen, Z., Chidthaisong, A., Gregory, J. M., Hegerl, G. C., Heimann, M., Hewitson, B., Hoskins, B. J., Joos, F., Jouzel, J., Kattsov, V., Lohmann, U., Matsuno, T., Molina, M., Nicholls, N., Overpeck, J., Raga, G., Ramaswamy, V., Ren, J., Rusticucci, M., Somerville, R., Stocker, T. F., Whetton, P., Wood, R. A., and Wratt, D. (2007). *Technical Summary. In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)].* Cambridge University Press, Cambridge, UK.

Stedman, J. R. (2004). The predicted number of air pollution related deaths in the UK during the August 2003 heatwave. *Atmospheric Environment*, 38:1087–1090.

Synnefa, A., Santamouris, M., and Akbari, H. (2007). Estimating the effect of using cool coatings on energy loads and thermal comfort in residential buildings in various climatic conditions. *Energy and Buildings*, 39:1167–1174.

Synnefa, A., Santamouris, M., and Livada, I. (2006). A study of the thermal performance of reflective coatings for the urban environment. *Solar Energy*, 80(8):968–981.

The Institute of Environmental Management and Assessment (2009). Adapting to climate change survey. Lincoln, UK.

Three Regions Climate Change Group (2008). Case study - block of flats. www.london.gov.uk/trccg/casestudies/block/index.jsp.

U.K. Government (2011). Departmental adaptation plans. Available online from: http://www.defra.gov.uk/environment/climate/programme/across-government.htm Last accessed 26th March 2012.

UK Meteorological Office (2011a). August 2003 - Hot spell. Online: www.metoffice.gov.uk/climate/uk/interesting/aug03maxtemps.html Last accessed 26th March, 2012.

UK Meteorological Office (2011b). Heat wave threshold temperatures. Available from: www.metoffice.gov.uk/weather/uk/heathealth/ Last accessed 25th March, 2012.

UK Meteorological Office (2011c). MIDAS Land Surface Stations data (1853-current). Available from http://badc.nerc.ac.uk Last accessed 16th March, 2011.

UKCIP (2011). UK Climate Projections: Heatwave Available online: http://ukclimateprojections.defra.gov.uk/content/view/563/690/ (Last accessed 24th March, 2012).

U.S. Department of Energy (2010). EnergyPlus Version 6 software and documentation available from: http://apps1.eere.energy.gov/buildings/energyplus/ Last accessed 25th August, 2011. Note: Version 6 is no longer available, this link will now allow download of Version 7 (25th March, 2012).

U.S. Department of Energy (2011a). Auxiliary EnergyPlus Programs. Download: http://apps1.eere.energy.gov/buildings/energyplus/pdfs/auxiliaryprograms.pdf Last accessed 25th March, 2012.

U.S. Department of Energy (2011b). EnergyPlus Testing with Building Thermal Envelope and Fabric Load Tests from ANSI/ASHRAE Standard 140-2007. Available online: http://apps1.eere.energy.gov/buildings/energyplus/energyplus_testing.cfm Last accessed 21st March, 2012.

U.S. Department of Energy (2011c). *Getting Started with EnergyPlus*. Available online: http://apps1.eere.energy.gov/buildings/energyplus/pdfs/gettingstarted.pdf Last accessed 25th March, 2012.

U.S. Department of Energy (2012). EnergyPlus Testing and Validation. Online: http://apps1.eere.energy.gov/buildings/energyplus/energyplus_testing.cfm Last accessed 21st March, 2012.

Vandentorren, S., Bretin, P., Zeghnoun, A., Mandereau-Bruno, L., Croisier, A., Cochet, C., Riberon, J., Siberan, I., Declercq, B., and Ledrans, M. (2006). August 2003 heat wave in france: Risk factors for death of elderly people living at home. *European Journal of Public Health*, 16(6):583–591.

Watco (2012). Solar Reflective Coating Data Sheet. Online: www.watco.co.uk Last accessed 25th March 2012.

Watkins, R., Palmer, J., Kolokotroni, M., and Littlefair, P. (2002). The london heat island: results from summertime monitoring. *Building Services Engineering Research and Technology*, 23(2):97–106.

Wright, A., Young, A., and Natarajan, S. (2005). Dwelling temperatures and comfort during the August 2003 heat wave. *Building Services Engineering Research and Technology*, 26(4):285–300.

Zero Carbon Hub (2010). Carbon compliance for tomorrow's new homes: A review of the modelling tools and assumptions. overview of findings and recommendations. Available online: www.zerocarbonhub.org Last accessed 25th March, 2012.

Zhang, Y. (2009). "Parallel" EnergyPlus and the development of a parametric analysis tool. In *Eleventh International IBPSA Conference*, pages 1382–1388, Glasgow, Scotland.

Zhang, Y. and Korolija, I. (2010). Performing complex parametric simulations with jEPlus. In *SET2010 - 9th International Conference on Sustainable Energy Technologies*, Shanghai, China.